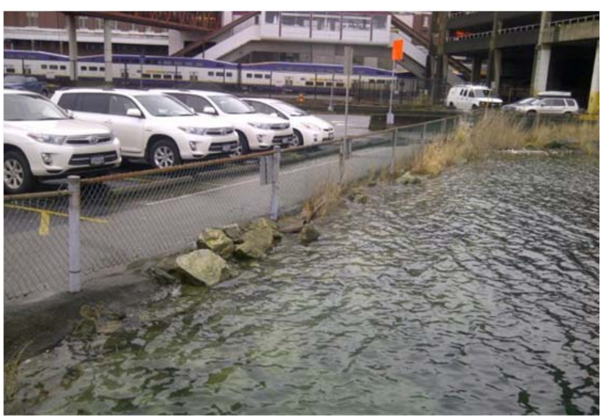
CITY OF VANCOUVER
COASTAL FLOOD RISK ASSESSMENT

FINAL REPORT

Prepared for:

CITY OF VANCOUVER

CITY OF VANCOUVER
453 West 12th Avenue
Vancouver, BC, V5Y 1V4



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CITY OF VANCOUVER COASTAL FLOOD RISK ASSESSMENT

FINAL REPORT

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EXECUTIVE SUMMARY

Sea level has increased over the last century and is expected to rise at an accelerated rate over the next century. The City of Vancouver (the City) retained the consulting team to assess the potential for present and future flooding along four shoreline zones in view of the projected sea level rise (SLR). Detailed hydrologic-hydraulic modelling investigations were carried out for five scenarios, including simulating the base case (2013) and then conditions in 2100 and 2200. The City wanted to evaluate future flooding using a joint probability modelling methodology. Of particular interest was defining the floodplain extents, flood depths and flood construction levels (FCLs) to assess vulnerable areas and the consequences to people, property and infrastructure. The study is a first step in an overall strategy for flood response and its results feed into Phase 2 of the project, which will explore options for mitigating and adapting to the flood risk across the City.

Over the course of the project, the team has recognized the many uncertainties and gaps in the process of developing a Coastal Flood Risk Assessment (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 report highlights the many obstacles and gaps in the assessment, but also alludes to the inherent value of the process and results:

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 include 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 the 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. Each interaction with the stakeholders has hopefully resulted in increased awareness about 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, while others will merely be identified and acknowledged.

Five scenarios were developed in consultation with the City and the Technical Advisory Group that encompass possible future SLR conditions to 2200 combined with design storm events:

- Scenario 1, Year 2013, 0.0 m SLR, 1:500 year storm hazard
- Scenario 2, Year 2100, 0.6 m SLR, 1:500 year storm hazard
- Scenario 3, Year 2100, 1.0 m SLR, 1:500 year storm hazard
- Scenario 4, Year 2100, 1.0 m SLR, 1:10,00 year storm hazard
- Scenario 5, Year 2200, 2.0 m SLR, 1:10,000 year storm hazard

A continuous simulation (joint probability) approach was taken to establish the ocean levels affected by meteorological and oceanographic conditions corresponding to the selected return periods for each scenario. The approach is statistically defensible and reduces the conservatism inherent in the method presented in the 2011 Provincial Guidelines.

Ocean levels were then used as the boundary conditions for the overland flood models. The City was divided into four modelling zones, each having similar exposure and characteristics. Modelled flood levels were found to be relatively consistent across each zone for each scenario. Maps were developed that show the flood extents and flood depths spatially under each scenario.

Flood Construction Levels (FCLs) were set based on Scenario 3, chosen in consultation with the City and Technical Advisory Group. A freeboard of 0.6 m was added to Scenario 3 modelled flood levels to give an FCL of 4.6 m Geodetic Datum (GD), consistent across the four flood-prone zones. A wave boundary was delineated and an additional 0.3 m wave effect allowance is to be applied seaward of the boundary to form the FCL in the wave zone (or alternatively a site-specific study is to be completed). As a point of comparison, an FCL of 3.5 m GD, assumed to have a return period of 1 in 200 years, was used by the City prior to the recognition that SLR will affect future conditions.

Areas within the City that are vulnerable during a Scenario 3 coastal flood event were assessed and "hot spot" maps produced. The mapping showed that emergency routes such as Main Street and Pacific Boulevard will be partly inundated. Important transportation hubs such as Waterfront Station could potentially be vulnerable. Current planned Gathering Areas in the Downtown core will have to be redefined as some will be flooded. Cultural and historic sites in Gastown and Chinatown will flood. Community services and housing centres in the Downtown Eastside, particularly between Carrall St and Main St, as well as school and childcare spaces in the Olympic Village, International Village and near Terminal Avenue are vulnerable, assuming no flood mitigation measures are taken.

A stormwater assessment of False Creek Flats in Zone 2 indicated that a decrease in the capacity of the system can be expected with SLR, and without mitigation, flooding extents and depths (of the stormwater system) will increase. The most effective solution to mitigating sea level backwater impacts is likely to be the addition of pumping capacity to convey flows over a floodwall at the system outlets. The pump station needed to provide this pumping capacity would be large, requiring a maximum pumping rate on the order of 10 m^3/s if a forebay volume of 12,500 cubic metres were provided.

Hazus modelling was undertaken as a way of quantifying damages for a consequence assessment for flood prone areas in Vancouver. Hazus modelling is the best available tool for flood consequence assessment in Canada and provides insight into expected damages and losses that might be experienced by the City. In particular, it shows that a coastal flood event in Vancouver will have a large impact on people, first and foremost, displacing thousands of families in the short term, and causing disruption to hundreds of families while their residences are cleaned and repaired post-disaster. The results also show that there are significant losses expected from building damage as a result of coastal flooding. Even under Scenario 1 conditions, large losses are anticipated. A considerable proportion of the losses are ascribed to content and inventory damages, which is not surprising given the number of industrial buildings that are inundated. Spatially, the Fraser River floodplain is shown to have significant losses under present-day and future flood scenarios in both the residential Southlands area and in the industrial lands further east. Granville Island is another hotspot for building losses, particularly under the 1.0 m SLR scenarios.

The results of the study and the prepared mapping can be used to support identification and development of mitigation and adaptation options, both structural and non-structural, as the project moves into Phase 2. An update of the FCL within the City's bylaws based on the results will take effect on January 1, 2015.

The results of the study provide a flood hazard baseline. If future scientific findings show that climate change is affecting SLR and storm intensities differently than assumed in this study, the impact of these changes can be compared to the baseline to better understand the potential variations in risk. The Hazus model should be updated as the algorithms are adapted to the Canadian context and as more applicable depth-damage curves are developed.

Mitigating and adapting to flood risks will be an ongoing process that will need to respond to climate conditions as they develop into the future and as new management tools evolve.

CREDITS AND ACKNOWLEDGEMENTS

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The authors would like to thank the City of Vancouver for initiating this study, making available extensive background information and providing advice and support through-out the study. The key City representatives were:

- Tamsin Mills, MCIP, RPP — Project Manager
- Brad Badelt, P.Eng, — Project Manager
- Dane Doleman, P.Eng. — Structures Engineer
- Dan Campbell — GIS
- Jim O'Leary — GIS

Port Metro Vancouver also collaborated on this study, and key representatives include:

- Mo Mofrad, P.Eng. — Project Engineer
- Sean Smith — Asset Management GIS Integration Specialist

The following Northwest Hydraulic Consultants Ltd (NHC) personnel participated in the study:

- Bruce Walsh, P.Eng. — Principal-in-Charge
- Charlene Menezes, P.Geo. — Project Manager
- Clayton Hiles, P.Eng. — Project Engineer – Ocean Modelling
- Vanessa O'Connor, P.Eng. — Project Engineer – Hydraulic Modelling
- Sarah North, GISP — GIS Specialist
- Derek Stuart, P.E. — Senior Engineer – Stormwater Assessment
- Monica Mannerström, P.Eng. — Report Review

The following Arlington Group personnel provided sub-consultant services:

- Graham Farstad, MCIP — Senior Planner – Vulnerability Assessment
- Amanda Grochowich — Assistant Planner – Vulnerability Assessment

The following Ebbwater Consulting personnel provided sub-consultant services:

- Tamsin Lyle, P.Eng., MRM — Flood Management Specialist – Consequence Assessment

Through the course of the study, meetings were held with a Technical Advisory Group (TAG). The purpose of these meetings was to provide an update on the progress of the study and to obtain input and direction on some of the key technical aspects of the project. The TAG consisted of technical representatives from the City of Vancouver, Metro Vancouver, Ministry of Forests, Lands and Natural Resource Operations, Port Metro Vancouver, Natural Resources Canada, University of British Columbia and the Canada Mortgage and Housing Corporation.

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List of Acronyms

AEP	Annual Exceedance Probability
CD	Chart Datum
CFRA	Coastal Flood Risk Assessment
CHS	Canadian Hydrographic Service
CPR	Canadian Pacific Railway
DEM	Digital Elevation Model
DFL	Designated Flood Level
DIM	Direct Integration Method
DTES	Downtown Eastside
EC	Environment Canada
ENSO	El Nino Southern Oscillation
EPA	Environmental Protection Agency
EST	Empirical Simulation Technique
FCL	Flood Construction Level
FCRP	Flood Construction Reference Plane
FEMA	Federal Emergency Management Agency
GCM	Global Climate Model
GD	Geodetic Datum
GVRD	Greater Vancouver Regional District
HHWLT	Higher High Water Large Tide
IPCC	Intergovernmental Panel on Climate Change
NEU	Neighbourhood Energy Utility
NRCS	Natural Resources Conservation Service
PDO	Pacific Decadal Oscillation
PMV	Port Metro Vancouver
PST	Pacific Standard Time
RSLR	Relative Sea Level Rise
SLR	Sea Level Rise
SWMM	Storm Water Management Model
TAG	Technical Advisory Group
UDF	User Defined Approach

1 INTRODUCTION

1.1 BACKGROUND

The Province of BC issued Guidelines in 2011 on flood hazard land use management that included direction related to sea level rise (SLR). Studies by Ausenco Sandwell (2011a, 2011b), commissioned by the Province, indicate that there will be a significant impact to coastal BC over the next century. Based on a review of scientific literature, global sea level rise from the year 2000 was estimated to be in the order of 1 m by the year 2100 and 2 m by 2200. The City of Vancouver (the City) recognises that being a coastal city with limited flood protection infrastructure, the risks can be significant, and that the hazard and consequence posed by anticipated future coastal and river flooding may be better dealt with by using a combination of adaptation strategies, land-use changes and structural and non-structural approaches. Prior to developing such recommendations, the City sought to understand the potential hazard posed by future floods, vulnerabilities in the affected areas and anticipated consequences.

The City retained a team of consultants to identify and quantify the people, property and infrastructure at risk of damage as a result of sea level rise, and to develop policy options that can minimize the hazard, exposure, or vulnerability of residents and property at risk.

As part of a two-phase project, the present Phase 1 work focuses on defining the flood hazards, vulnerabilities and consequences for the City. Outcomes of this work will help to shape Phase 2, which is aimed at developing adaptation options and implementation plans for the future that can be integrated into land use planning and development policies. The key tasks for Phase 1 were:

- To better define the conditions of flooding given several sea level rise scenarios and to quantify the probabilities of occurrence, extent, depth, velocity and duration of such flooding.
- To understand the flood hazards associated with the simultaneous occurrence of high ocean levels and large stormwater runoff.
- To identify infrastructure, services and populations at risk and estimate potential consequences in terms of value and disruption.
- To inform the amendment of flood-proofing policies that can minimise the hazard, exposure or vulnerability of residents and property at risk.

1.2 SCOPE OF WORK

The main goal of the study was to assess the effects of the projected sea level rise combined with selected design events on the City's floodplain in order to develop appropriate future management strategies for flood prone areas. To accomplish this goal, a key component was to develop a robust, scientifically sound approach for defining the probability of occurrence of extreme flood events due to the combination of tides, waves and storm surge.

Specific tasks outlined in the Terms of Reference included:

- Item 1 - Data documentation – of infrastructure at risk under various scenarios and the collation of physical data.
- Item 2 - Hazard Analysis and Mapping – analysis of the hazards under different scenarios and their mapping using a joint probability approach.
- Item 3 - High-Level Vulnerability Assessment – a high-level vulnerability assessment of those assets (including stormwater/sewer infrastructure) vulnerable to sea level rise under different scenarios.
- Item 4 - Consequence Assessment – undertake Hazus modelling to estimate the potential losses under the different scenarios.

1.3 APPROACH

For the City, the future flooding hazard is a complex function of sea level rise and the frequency of storm events. As such, the study needed to consider flooding for a range of potential events and time-scales. To do so, five scenarios were chosen to bound the present and possible future conditions/scenarios.

Traditional approaches to flood hazard assessment consider only one discrete hazard type or return period at a time and do not reflect the true hazard level associated with multiple sources of flooding or complex climate change scenarios. A joint probabilistic approach to flood hazard that considers multiple pathways being coupled with sea level rise, is the approach taken in this study for establishing the ocean boundary conditions. The approach involves assessing the joint probability of the individual sea level components using a long historic record, and then carrying out an extreme value analysis to determine the design level for each scenario's return period event. This approach removes the challenge associated with specifying design conditions based on the projected extremes of individual water level components or speculating on the probability of the combined event. It also offers the advantage of producing statistically defensible design levels, without introducing added conservatism.

The ocean conditions established for each scenario were then used as the boundary conditions for overland flood modelling of the City's affected coastal areas. The urban environment of the City posed a challenge because of the shallow depths and complex flow paths created by roads, buildings and other structures on the floodplain. However, the detailed model resolution afforded by LiDAR data meant that two-dimensional numerical modelling to calculate depth and velocity components could be reliably carried out at each mesh node.

Once the flood hazard was defined by the overland flood levels for the selected scenarios, flood risk could be assessed. The assessment involved taking the anticipated depth and extents of the flood and combining it with information about vulnerable elements in the flood path. A vulnerability assessment was undertaken based on information provided by the City and other stakeholders on people, environment, infrastructure and economic considerations in the flood-prone areas. By combining the two datasets of hazard and vulnerability, potential losses due to flooding were identified through consequence modelling using Hazus-MH software. Depth-damage curves within Hazus, originally developed for the US, have their limitations in the Canadian context but allow calculation of direct losses in the flood-prone areas. Indirect losses were interpreted based on an understanding of potential cascading effects within the City. Identification of the flood hazard, and subsequent assessment of vulnerabilities and consequences, allows the City to move forward with flood management and land-use planning and development policies in Phase 2.

1.4 REPORT ORGANIZATION

In addition to this introductory Section 1 the following report sections address the various study components.

Item 1 – Data

> Section 2 provides a description of the site, background data and history of past flood events and Section 3 presents climate change scenarios to be considered.

Item 2 – Hazard Analysis and Mapping

> The coastal and hydraulic modelling for Burrard Inlet is outlined in Sections 4 and Section 5. The hydraulic modelling for the Fraser River North Arm is presented in Section 6. Mapping and a discussion of the resulting flood level extents and depths is provided in Section 7.

Item 3 – High-Level Vulnerability Assessment

> The vulnerability assessment, including the stormwater assessment, is discussed in Section 8.

Item 4 – Consequence Assessment

> The consequence assessment is dealt with in Section 9.

Conclusions and recommendations are in Section 10. Suggested further investigations are described in Section 11, with references listed in Section 12. For clarity and convenience, a list of definitions is provided in a glossary of terms in Section 13.

Six annexes are contained at the end of the report that provide further details on various parts of the study:

- Annex A lists available data collected for the study, and GIS data prepared during the study.

- Annex B contains coastal model development details.
- Annex C contains discussion of wave measurements and ocean model validation.
- Annex D contains overland model development details.
- Annex E contains the Vulnerability Assessment reporting.
- Annex F contains the Consequence Assessment reporting.

Digital files prepared during the study (Table A.3 in **Annex A**) are included as a final deliverable. These data files are provided on an external hard drive, along with a transmittal letter describing its contents.

2 SITE DESCRIPTION

2.1 PHYSICAL SETTING

Vancouver is part of the Uplands (Ice Age sediments) that lie between the Coast Mountains to the North and the Fraser Lowland (modern deltaic sediments) to the south. Glacial retreat following the Fraser Glaciation exposed the region and left layered gravel, sand and silt on the surface (Holland, 1976). The sea level rise due to glacial melting submerged the valley resulting in the creation of fjords such as Burrard Inlet and its extension, Indian Arm. Since the disappearance of the ice sheet, the land has been undergoing isostatic rebound.

The City is flanked to the north by Burrard Inlet, to the west by the Strait of Georgia, and to the south by the North Arm of the Fraser River (**Figure 1**). Of a number of watercourses that once ran through the City, only two visible streams remain; the lost streams have been culverted, built over or filled in. Instead, in the present highly urbanized environment, there is an extensive network of storm sewer infrastructure in the municipality. Flooding in the city therefore originates from either coastal flooding or stormwater/sewer system overflow, or both.

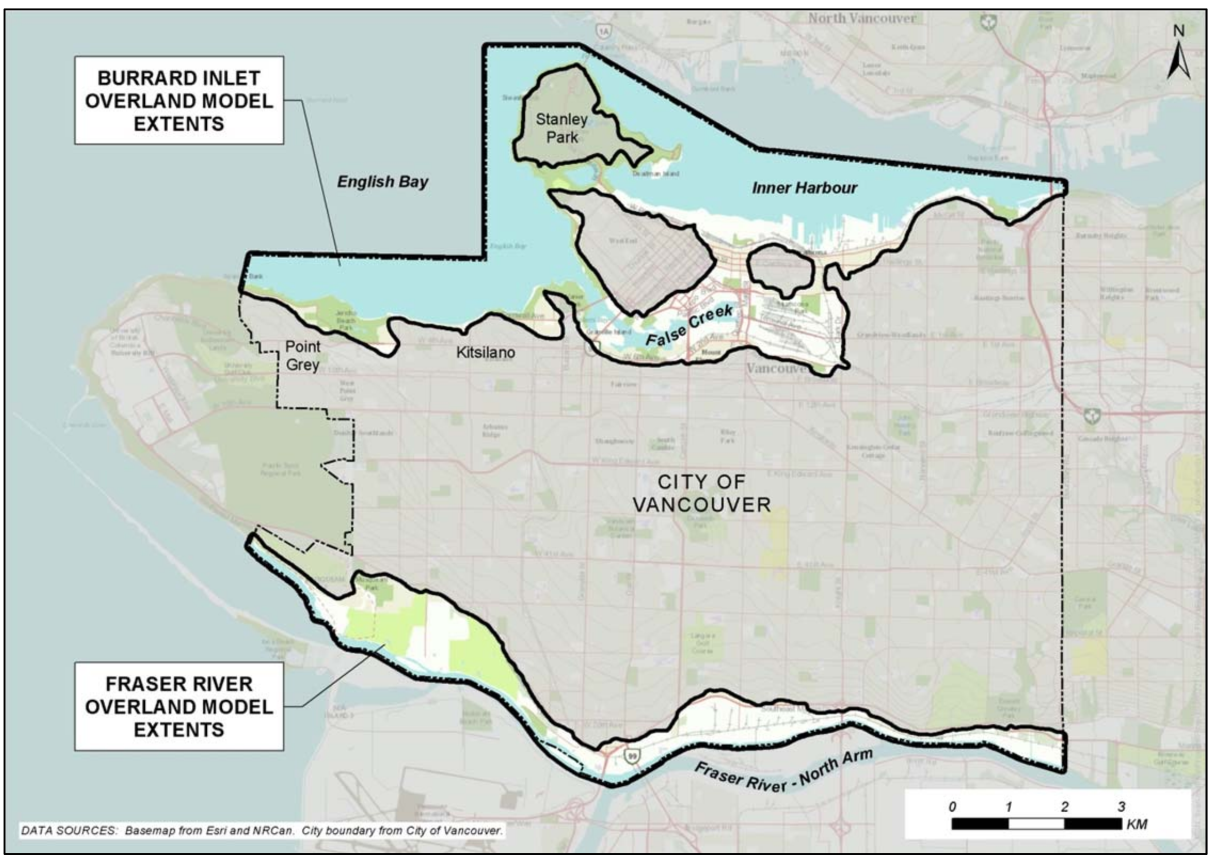

Figure 1. Study areas for City of Vancouver Coastal Flood Risk Assessment.

2.1.1 Point Grey – Kitsilano

The shoreline from Point Grey to Kitsilano Point is along the northern boundary of the City and oriented in an east-west direction. Although there are homes and mixed-use commercial, the area primarily has a recreational land use, with three main beach parks found along the shoreline: Spanish Banks/Locarno Beach, Jericho Beach Park and Kitsilano Beach Park. It faces the ocean, more specifically, the Strait of Georgia and as a result is exposed to waves from the northwest. Existing flood protection is limited along this section of shoreline: the western terminus of the seawall is at Kitsilano Beach, and west of that, riprap along the shoreline is discontinuous and of varying quality. Along the sections of shoreline fronted by narrower beach area, particularly near Locarno Beach, the ground elevation rises by 10 to 15 m a variable distance from shore, and land use in the upland consists mainly of low-density residential.

2.1.2 False Creek

False Creek is a short inlet extension of Burrard Inlet that lies west of Kitsilano Point. While it has a relatively more sheltered geography, the seawall runs along the entire shoreline of this water body. Granville Island is a small island situated off its southwestern shore. Historically, the head of False Creek ran to Clark Drive, but the easternmost part was filled in west to Main Street – now referred to as False Creek Flats – to create new land for the rail yards and terminals. Formerly regarded as the industrial heartland of Vancouver, the area around False Creek has been transformed in recent decades to a dense residential community, particularly along its north and east shores. A well-developed network of storm sewers in these upland urban areas discharges into False Creek.

2.1.3 English Bay – Stanley Park

North of the mouth of False Creek, the shoreline faces the ocean once more at English Bay. The shoreline at English Bay continues north and east around Stanley Park, a large forested area next to the City's downtown core. The seawall continues along its entire shoreline offering erosion and flood protection during storms and recreational access year-round. Around much of the northern portion of the Park's shoreline, the topography consists of steep cliffs, with the exception of the relatively flat low landscape in the area surrounding Lost Lagoon.

2.1.4 Inner Harbour

Along Burrard Inlet east of the Brockton peninsula of Stanley Park is an area known as the Inner Harbour. Land use in this area is highly variable: along the immediate shoreline are mainly industrial and transportation areas with the marinas, floatplane terminals, West Coast Express, SeaBus and SkyTrain terminals, as well as Port-related shipping and rail transport. Further inland, there is the commercial land use of the downtown core with dense residential towers to the west and low-income housing to the east. Much of the shoreline in the eastern portion of this zone is an extension of Vancouver's seawall which also serves a recreational purpose.

The area's many competing land uses have been made possible by land reclamation through infilling of near-shore areas. Docks and piers extend out into the open water. Elevated structures, parkades, and underground features, such as roads and tunnels add to the area's complexity.

2.1.5 Fraser River North Arm

The North Arm of the Fraser River is one of three arms of the river, and lies along the City's southern boundary. Flooding along this reach, close to the river mouth, is dominated by winter tides as opposed to freshet flooding of upstream reaches. Land use along the shoreline has historically been industrial, recreational, and low-density residential in the Southlands area. However, there is increasing development of higher density residential communities such as in the East Fraserlands. Flood protection along this reach consists of a mix of non-standard structural approaches, including use of rock revetments and retaining walls.

2.2 Flood Hazards

Potential flood hazards in the Vancouver coastal-dominated system that were assessed in the study include:

- Overland inundation of Burrard Inlet areas during extreme high-water conditions (high tide, storm surge and wave runup).
- Influence of extreme winter tide on Fraser River water levels.
- Influence of rainstorms on overflow of the sewer network.

It is worthwhile to note that extreme water levels in the lower estuary of the Fraser River are governed by the occurrence of high tides and storm surge in the winter season, rather than high discharges during the freshet.

2.3 History of Floods

Data collected by the City on historical flooding events is limited to local flooding of property induced by non-coastal flooding mechanisms, such as backflow of pipes. There is, however, a history of winds and extreme tides in winter causing flooding along the City's shoreline. Notable coastal events compiled by SFU's ACT (2012) for Vancouver include:

- December 15th, 2006 – peak water levels measured 4.48 m CD[1] and coincided with 67 km/h winds from the west, and caused significant wind-induced damage in Stanley Park but no reported flooding.

[1] Conversion from Chart Datum (CD) to Geodetic Datum (GD) at Point Atkinson is -3.1 m.

- December 15th, 1977 – peak water levels measured 5.48 m CD and were preceded by 20 km/h winds from the northwest, and caused seawall breach at Kitsilano Beach and flooding of Kitsilano Pool.
- December 5th, 1967 – peak water levels measured 5.57 m CD and coincided with 29 km/h winds from the southwest, caused flooding at the intersection of Cambie St. and Kent St., Water St., and the foot of Burrard Bridge.
- October 12th, 1962 – peak water levels measured 5.18 m CD and coincided with 35 km/h winds from the southeast, associated with landfall of Typhoon Freda, it caused extensive wind damage but no reported flooding.

More recently, in December 2012, there was a King Tide event that caused flooding along the Burrard Inlet shoreline:

- December 17th, 2012 – the peak water level was estimated to be 2.66 m Geodetic Datum (5.76 m CD) in the Point Grey to Kitsilano reach and westerly winds caused flooding at Stanley Park and Kitsilano Beach (Storm Surge Almanac, 2013).

The December 2012 event was statistically computed to be about a 1:50 year event in the Point Grey to Kitsilano area, in part because it unusually coincided with large waves that increased the effective water level. The peak tide level associated with the event, however, occurs on average once every three years. Granville Island is one of the areas that regularly experiences minor flooding during these King Tide events (Technical Advisory Group, 2014).

2.4 AVAILABLE INFORMATION

Extensive GIS background information is available for the project area. Table A.1 in **Annex A** summarises topography, imagery, hydrography, land use, socio-economic and administrative information received from the City, Port Metro Vancouver (PMV) and other sources. The information includes data on building footprints, land-use classification, stormwater networks, previous flood mapping, key infrastructure locations, in addition to reference data on roads, railways and administrative boundaries. Also included is ocean bathymetry and orthophotography.

Tidal levels, wind and wave measurements, were acquired from various government agencies and are summarized in Table A.2 in **Annex A**.

3 CLIMATE CHANGE SCENARIOS

The consensus view from organizations such as the Inter-governmental Panel on Climate Change (IPCC) is that the global climate system is warming, and the expectations are that the global annual mean temperature will rise more than 3°C this century. Continued warming and changing of precipitation patterns, and associated rising seas, will have a large effect on hydrological processes, with significant implications for the economy, infrastructure, and eco-systems of British Columbia (Rodenhuis et al., 2007; IPCC, 2007; IPCC, 2013; Arlington, 2013).

3.1 SEA LEVEL RISE

The sea level rise policy for BC recommends assuming a 1 m rise in global mean sea level between the year 2000 and 2100 (Ausenco Sandwell, 2011a) as show in **Figure 2**.

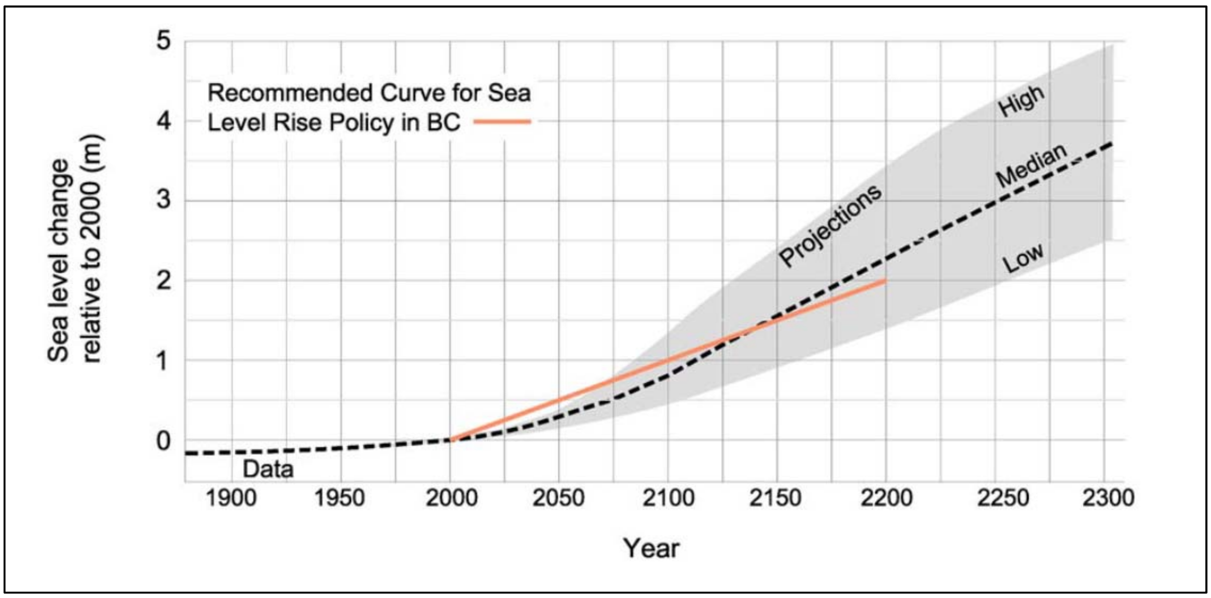

Figure 2. Sea level rise policy curve for BC (Ausenco Sandwell, 2011a).

While the policy implies an assumption of a linear 10 mm/year rise in sea level from 2000 to 2100, it is clear that this assumption overstates actual sea level rise early in this period. Recent analyses based on satellite altimeter measurements (**Figure 3**) show a more or less steady global mean sea level rise from 1993 to 2013 of 3.2 ± 0.4 mm/year.

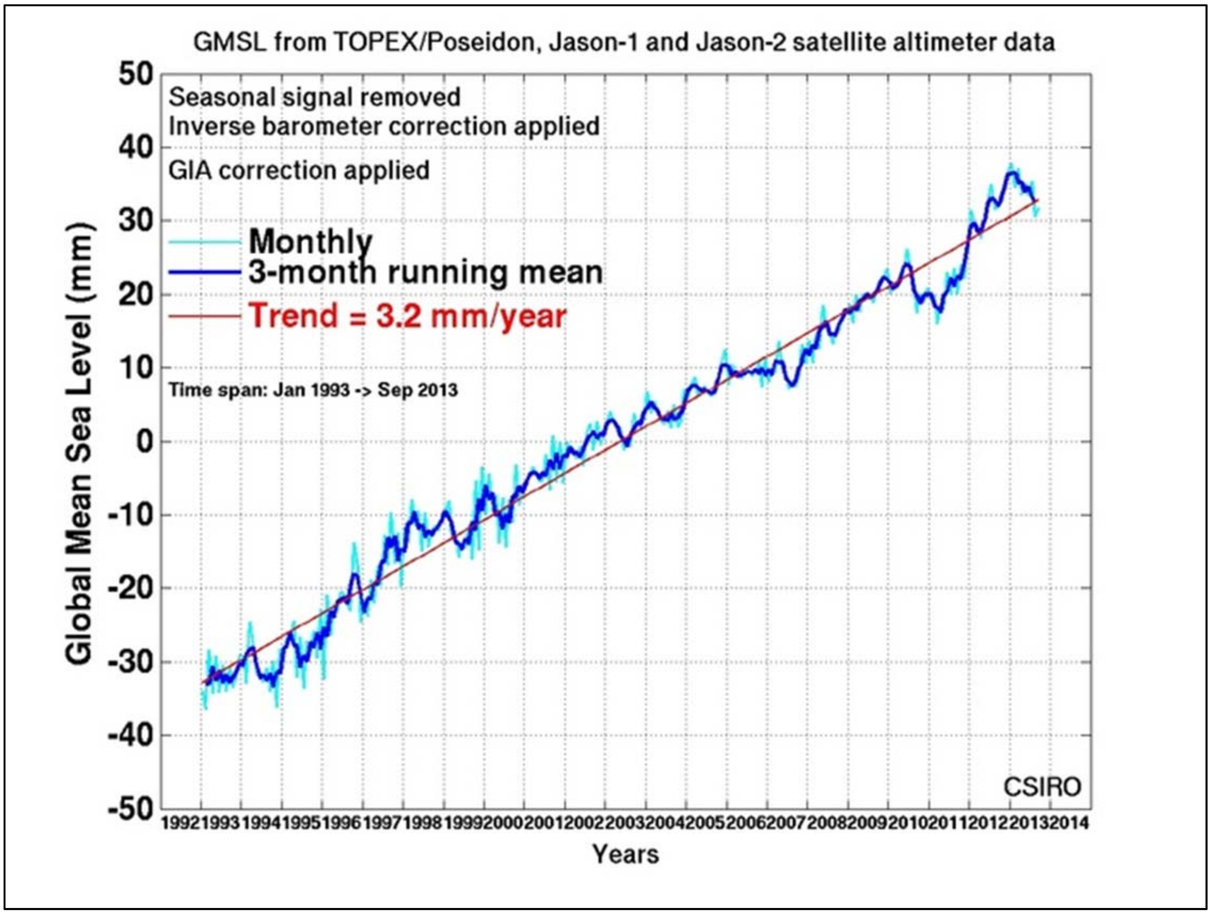

Figure 3. Global mean sea level, 1993-2013[2].

For the present study, year 2010 was adopted as the nominal baseline condition. Ocean level data was adjusted as necessary (see **Section 4.2**) to produce stationary ocean level time series representative of the 2010 mean sea level. Based on **Figure 3**, there was an approximately 0.03 m absolute sea level rise from 2000 to 2010. To ensure consistency with draft sea level rise policy and provincial guidelines, a linear 0.97 m rise in absolute sea level was assumed from the 2010 base condition to 2100 to give a total 1.0 m rise from 2000 to 2100.

As part of this study, the impacts of sea level rise were assessed for the years 2100 and 2200. **Map Set 1** shows the extents of flooding in 2100 under Higher High Water Large Tide (HHWLT) conditions, without a concurrent storm event. This was obtained by combining a 2.0 m HHWLT with an SLR of 1.0 m to yield flood extents at elevation 3.0 m GD. Under these conditions, sections of

[2] CSIRO Marine and Atmospheric Research, Australia - http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html, accessed 21 Apr 2014.

Jericho Beach, Kitsilano Beach, Granville Island, Olympic Village, Second Beach and Port Lands would be affected.

It should be recognized that there is significant uncertainty in sea level rise projections with a range in the rise presented in the draft provincial sea level rise policy and shown in **Figure 2**, from about 0.5 m to 1.3 m by 2100 and 1.4 m to 3.4 m by 2200. A 1.0 m sea level rise estimate by 2100 is in the upper range of projections and allows planners to be ahead of the curve. Whereas a 2.0 m rise estimate by 2200 is towards the low to mid-range of projections, it should be recognized that there is considerable uncertainty with estimates nearly two centuries away. Given these uncertainties, reliance on interpolation of simulation results, rather than detailed simulation of finer increments of sea level rise, is considered to be a reasonable and an appropriate approach for intermediate and long-range planning purposes. It is recommended that the City monitor changes in sea level rise estimates and adapt their flood management plans accordingly.

3.2 STORM FREQUENCY AND INTENSITY

While some climate change studies have indicated possible future increases in the frequency and intensity of storms, implying possible future increases in wave climate severity and storm surge, there is at present little consensus on such impacts. The policy discussion paper (Ausenco Sandwell, 2011a, pg. 3) states:

> *At the present time, scientific information on the expected changes in storms approaching British Columbia coastal waters and their characteristics, specifically on the intensity of the storms, their related wave conditions and the associated storm surges in the future, is only starting to emerge. Based on the available information it appears reasonable to conclude that no significant change is expected in coastal BC waters; however, further investigations are warranted to fully assess the regional implications and to further assess future trends.*

Accordingly, potential future increases in storm frequency and intensity were not considered in this study. If future scientific findings show an increase in storm intensity with climate change, then it is likely that the storm surge component of the ocean level series could be amplified to reflect such impacts.

3.3 PRECIPITATION

Most Global Climate Models (GCMs) show wetter winters and drier summers over much of western Canada and the US Pacific Northwest with future climate change. Increased winter precipitation would increase stormwater loading and exacerbate flooding already affected by sea level rise. The magnitude of future change in precipitation is however uncertain.

APEGBC has recently developed "*Professional Practice Guidelines for Legislated Flood Hazard and Risk Assessments in a Changing Climate in BC*" (2012) which includes a discussion on climate change impacts on precipitation. Preliminary reference is made to peak flow increases in the order of 10%.

It is recommended that potential precipitation changes under climate change be investigated as part of future work. This would only affect the precipitation applied to the hydrologic simulation for the stormwater assessment in Item 3, though no such scaling of precipitation is reflected in the included results for that task or have been evaluated to date.

3.4 GROUND ELEVATION CHANGES

The land surface across Metro Vancouver is changing due to two processes: isostatic adjustments and delta subsidence. The latter is not relevant to the City as it does not lie on the Fraser River delta, but the former is a factor.

An ongoing study by Hill et al. (2013) at Roberts Bank employed InSAR[3] technology to detect surface movement over several years, with the capability of resolving movements on the order of about 1 mm/year. Rates of uplift or subsidence were mapped across Metro Vancouver (**Figure 4**) and show that the majority of the land in Vancouver is experiencing virtually no change with a rate of 0 ± 0.5 mm/year. However, select areas are subsiding at a rate of 1 ± 0.5 mm/year, which amounts to 0.1 m of ground subsidence over a 100-year timespan. These areas include: Musqueum IR, Southlands, Fraser lands north of Mitchell Island, False Creek and Coal Harbour.

A recent unpublished study by Natural Resources Canada examined local variations such as these across Metro Vancouver on sea level rise estimates, and found that the 1.0 m estimate for sea level rise along the Vancouver shoreline is robust (Technical Advisory Group, 2013). Whereas ground elevation changes were not explicitly accounted for in the flood modelling, they should be taken into consideration in future planning.

[3] Interferometric Synthetic Aperture RADAR

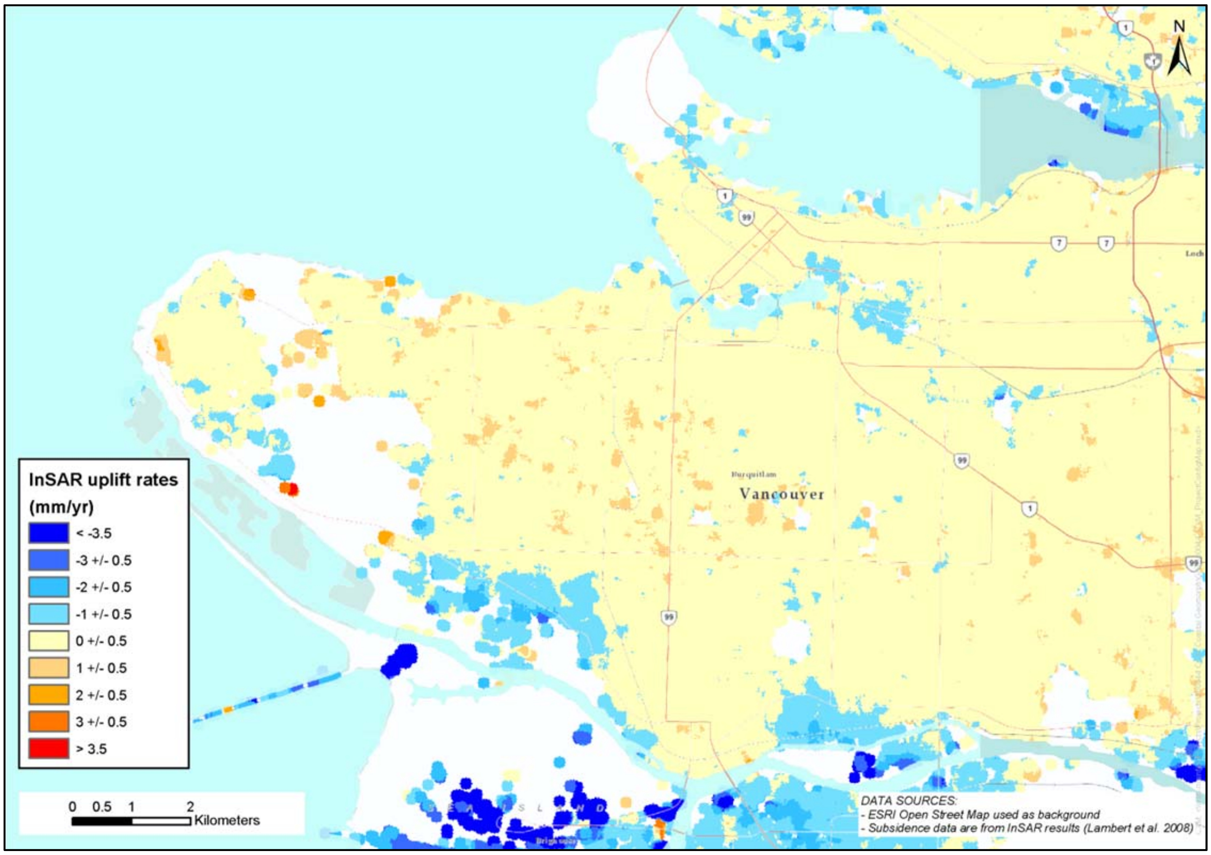

Figure 4. Map showing the rates of ground elevation change for the City of Vancouver (various sources - from Hill et al., 2013). Positive values indicate uplift and negative values indicate subsidence.

3.5 MODELLING SCENARIOS

Working with the project's Technical Advisory Group (TAG), a range of scenarios was developed that encompass possible future SLR conditions to 2200 combined with design storm events (**Table 1**).

Table 1. Selected modelling scenarios for the hazard assessment.

Scenario	Year	Sea Level Rise	Return Period	Method[4]
1	2013	0.0 m	1:500 year	
2	2100	0.6 m	1:500 year	Joint
3	2100	1.0 m	1:500 year	Joint
4	2100	1.0 m	1:10,000 year	Joint
5	2200	2.0 m	1:10,000 year	Joint

As was discussed in **Section 3.1**, SLR estimates for policy-setting in British Columbia include 1.0 m by the year 2100 and 2.0 m by 2200. Recent unpublished research by Natural Resources Canada using an empirical approach yielded SLR values of 30-50 cm for Vancouver by 2100, and with the addition of 0.3 to 0.6 m from a potential collapse of the West Antarctic ice sheet, result in an overall range of between 0.6 m to 1.1 m. SLR estimates of 0.6 m and 1.0 m fall at the lower and upper ends of this range (Technical Advisory Group, 2014). While the timing of 1.0 m SLR may occur before or after the year 2100, the four provinces in Atlantic Canada (Arlington Group, 2013), and many U.S. and European jurisdictions have used this increase in sea level for long-term planning purposes.

The return period is a measure of the average length of time in years for an event of a given magnitude to be equalled or exceeded, independent of SLR. Return periods of 500 years and 10,000 years were selected in consultation with the TAG to bracket reasonable values used around the world for regulatory purposes. In Europe, the Netherlands, which faces a significant coastal hazard, has adopted a safety standard of 1:10,000 for their ring dikes in exposed areas. Locally, an approximate 500-year return period (1894 flood of record) is used as the design flood on the Fraser River. A designated 1:500 year event also reflects the standard recommended in the recent coastal floodplain mapping guidelines for BC (Kerr Wood Leidal, 2011). In contrast, the regulatory flood in BC is a 1:200 year flood and all the other provinces (except Saskatchewan) have a lower standard of 1:100.

The return period concept can also be defined in terms of the likelihood of an event with a given return period occurring over a defined period of time, such as 20, 50 or 100 years. **Table 2** presents the computed probabilities of an event of a given return period occurring over a selected period of time. For the City, the year 2100 is being used as the planning horizon, which is roughly a 100-year period. The likelihood of a 500-year and 10,000-year event occurring sometime over a 100-year period is 18% and 1%, respectively.

[4] Here, 'Joint' refers to the continuous simulation approach – a method which accounts for the joint probability of individual sea level components.

Table 2. Approximate probabilities of exceedance for different return periods and exposure times.

Return Period (yrs)	Probability of Exceedance over Period of Time (yrs)							
	2	5	10	20	70	100	200	500
200	0.01	0.02	0.05	0.10	0.30	0.39	0.63	0.92
500	0.00	0.01	0.02	0.04	0.13	0.18	0.33	0.63
1000	0.00	0.00	0.01	0.02	0.07	0.10	0.18	0.39
10,000	0.000	0.000	0.001	0.002	0.007	0.010	0.020	0.049

4 Ocean Level Analysis

4.1 Purpose

The purpose of the ocean analysis was to specify the ocean conditions on which the calculation of Designated Flood Level (DFL) and Flood Construction Level (FCL) could be based. The following tasks were part of this analysis:

- Develop an understanding of the physical processes which contribute to high water level events in the City.
- Gather sufficient data to statistically describe the processes which contribute significantly to high water level events.
- Estimate the magnitude of low probability (1:500 year, 1:10,000 year) high water level events based on the available data.

In the approach taken in this work, the results of the ocean analysis are not used directly to calculate DFL and FCL. Rather, the results were used to provide boundary conditions to an overland flood and wave model which in turn provides the conditions necessary for calculating DFL and FCL.

Section 4.2 of this chapter provides a summary of the ocean conditions affecting coastal flooding in the City. **Section 4.3** describes two methods for estimating the magnitude of low probability water level events; one based on guidelines published by the Province of BC and another based on a continuous simulation approach suggested in FEMA guidelines for the Pacific Coast. **Sections 4.4** and **4.5** describe the various measured data-sets assembled for this work, the computational modelling performed to augment the measured data and how they were assembled into a continuous hind-cast of ocean conditions. **Section 4.6** summarises the use of a statistical model to estimate the magnitude of low probability, extreme water level events. **Section 4.7** describes how the estimates of extreme water level and data contained within the coastal hind-cast were used to synthesise boundary conditions for an overland flood and wave model. **Section 4.8** compares shoreline FCL calculations made using the Provincial Guideline method with the continuous simulation approach used in the current study.

For clarity and convenience, a list of definitions is provided in **Section 13 - Glossary**.

4.2 Background

A number of weakly correlated physical processes, or ‘components’, affect the ocean water levels around the City. Before going further it is worthwhile to review these processes and their relative impacts. In general, each component can be categorized as short term processes, acting over a period of a few minutes to a few days (tides, storm surge, wind setup, wave setup), or long term processes, acting over a year or more (El Nino, the Pacific Decadal Oscillation, sea level rise, subsidence/uplift).

Tides in the region are mixed semi diurnal with a range of about 5.1 m and a maximum elevation of 2.0 m GD. Tides are larger in the winter and smaller in the summer. The maximum tidal elevation occurs once every 18.6 years, but comes close to maximum elevation for a few tides each year. These yearly large tides are often referred to as 'King Tides'. Tides are typically the largest contributor to high water events in the City region.

Storm surge observed at Vancouver is usually associated with low pressure systems that propagate off the Pacific into BC coastal waters. Water levels associated with storm surge usually peak at less than 0.5 m but can be greater than 1 m on top of ambient water levels and persist for a few hours to a few days. Storm surge is usually the second largest contributor to high water events in the City region.

The Strait of Georgia is a semi-enclosed basin such that waves are entirely locally generated. Large waves are generated when high winds blow parallel to the axis of the basin. This means that west of the First Narrows, the City is most vulnerable to waves and winds coming from the North-West; east of the First Narrows, the shoreline bordering the Harbour is most vulnerable to waves from the North-East. Large wave breaking on the beach causes both a static increase in water level (wave setup) and a dynamic, oscillating variation in water level (wave runup). Wave setup and runup are primarily proportional to breaking wave height but also depend on wave period, direction relative to shore, and the shore slope and other characteristics. Wave setup is generally the third largest contributor to high water level events in the City region.

Wind setup is associated with strong local on-shore winds blowing over shallow water. The only area of the City with significant susceptibility to wind setup is False Creek, where wind setup reaches about 10 cm. Wind setup will endure as long as high winds blow on-shore over the shallow fetch, typically not more than a few hours. Wind setup is generally the fourth largest contributor to high water level events in the City region, but is more important than waves in the False Creek area.

Longer-term climate variation including the Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) also affect water levels in the Strait of Georgia. Variations of sea level with these oscillations are mostly due to fluctuations in water temperatures which cause thermal expansion and contraction of the sea water. These effects have been reported to influence water levels by as much as 40 cm (Bornhold et al., 2012). Approximately two full cycles of the PDO and many cycles of the ENSO have occurred since 1960. In practical applications the effect of these longer term variations is often lumped in with storm surge.

Sea level rise due to global climate change is an important factor driving this coastal hazard study. According to the IPCC (2013) report, globally sea levels have been rising at a rate of 3.2 mm/year since 1993 and about 1 mm/year over the last 100 years. Due to residual glacial and isostatic effects of the British Columbia Coast, relative sea level rise (RSLR) has been significantly less than the global mean. At Vancouver and Point Atkinson, tide gauge measurements have been used to estimate a RSLR rate over the last 60+ years of approximately 0.5 mm/year (Mazzotti et al., 2008).

Weather patterns in the Eastern North Pacific may change with global climate change and consequently the variation of components comprising ocean water level may also change. Waves, storm surge and local wind-setup are all driven at least in parts by winds. However, currently there is little evidence to suggest that extreme wind speeds will change significantly in the greater Vancouver area (Murdock et. al, 2012). Long term climate variations such as ENSO and PDO may shift due to climate change. The effect of ENSO/PDO changes on the BC coast are not well understood at this time, therefore it is difficult to account for their impact on extreme water levels (Bornhold & Thomson, 2012). Increased sea levels will affect the propagation and dissipation of tidal energy and therefore the tidal range, but this effect is anticipated to be small within the next 100 years.

Of the physical processes which affect water level, only the tides are deterministic. This means that we can calculate the specific level of the tides at a certain time well into the future. When water level measurements are made at tide stations, the measurements contain both the deterministic component of the tides and probabilistic component due to all of the other factors affecting sea level. It is notable that peaks in the various water level components do not necessarily coincide with one another. This is illustrated by **Figure 5**, in which each of the components of water level in False Creek during 2012 are separated into individual time-series, and the red boxes identify the five highest values in each time series. The distinction between deterministic and probabilistic components is important when considering the statistical methods for estimating the probability of extreme water level events.

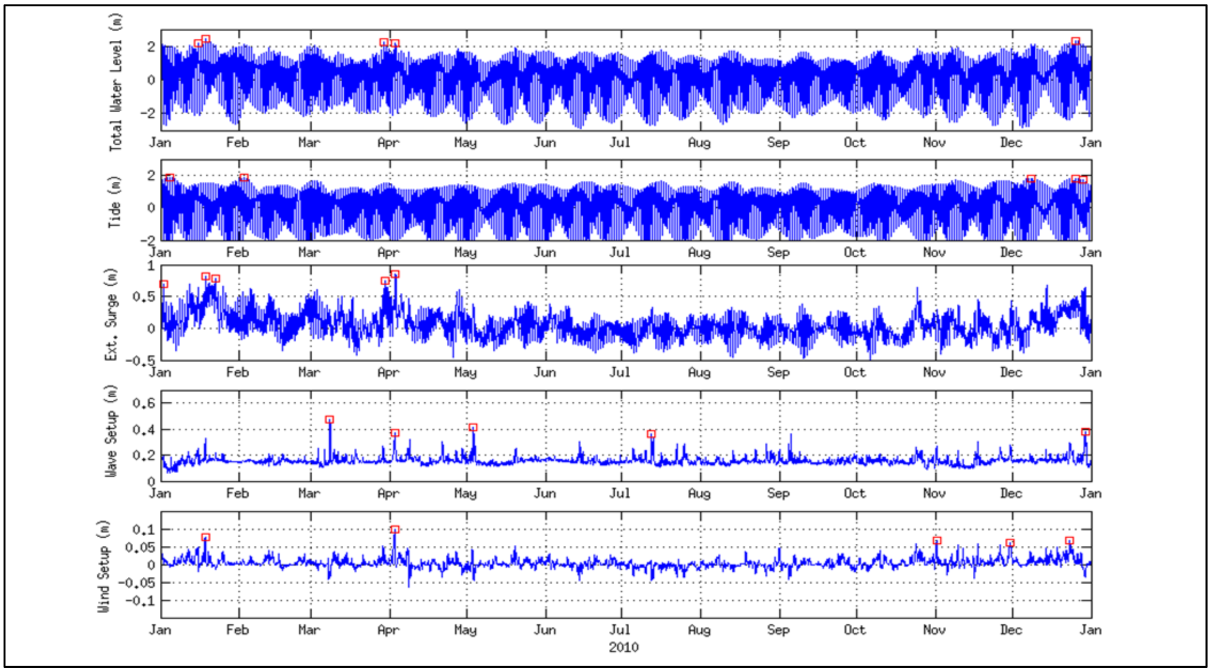

Figure 5. Time-series of each of the components of sea level at False Creek for the year 2012. Red boxes isolate the five highest values in the time-series.

4.3 Method of Approach

The purpose of the ocean analysis was to identify the ocean conditions from which the DFL and FCL could be calculated. These levels correspond to the ocean conditions of a very low probability storm (i.e. rare events). While different authorities specify different probabilities for the designated storm, the updated BC Provincial Guidelines suggest that an annual exceedance probability (AEP) of 0.01% or a return period of 10,000 years is appropriate for the City. This is significantly greater than previous Provincial documents which suggested a 200-year return period for the designated storm.

It is the responsibility of the local government to select a storm probability and corresponding level of risk that is appropriate for their community. Discussions with the project's TAG identified return periods of 500 years and 10,000 years as the storms to be investigated and have selected a 500-year return period to be used in the calculation of DFL and FCL. In this region, the 1:10,000 year event is not greatly larger than the 1:500 year event (approximately 3.2 m compared to 3.0 m).

In Canada, the historical record is rarely long enough to contain a storm with the target level of probability. In this case, it is required to estimate the conditions of the design storm from the available data. There are many methods to do this but most rely in some way on extreme value analysis.

Extreme value analysis is a branch of statistics addressing extreme deviations from the median of probability distributions. It seeks to assess, from a given ordered sample of a given random variable, the probability of events that are more extreme than any previously observed. Independent extreme events contained within the historical record are ordered and fit with a theoretical extreme value distribution. The magnitude of events with probability beyond the extent of the historical record can then be estimated with the fitted extreme value distribution.

Two methods for specifying the design storm and corresponding ocean conditions are covered here. The first is the method suggested in the updated BC Provincial Guidelines, the second is based on the continuous simulation approach similar to that suggested in the FEMA Guidelines for the Pacific Coast (FEMA, 2005). Tide, storm surge, wind setup and wave setup/runup are accounted for in both methods; future sea level rise is handled separately. The continuous simulation approach assumes that future events will be statistically similar in magnitude and frequency to past events. Implicit in this assumption is that event statistics are not significantly affected by climate change. As discussed in **Section 3.2**, based on the available information, it appears reasonable to conclude that no significant change is expected in coastal BC waters (Ausenco Sandwell, 2011a).

4.3.1 BC Provincial Guidelines

The BC Provincial Guidelines are actually a collection of documents (Arlington Group, 2013; Ausenco Sandwell, 2011a; Ausenco Sandwell, 2011b). This approach was not used in this work, but a discussion of it is provided here to give context for the method that was adopted.

In the Provincial Guideline documents, the Designated Flood Level (DFL), Flood Construction Reference Plane (FCRP) and Flood Construction Level (FCL) are defined as follows:

> DFL = Future Sea Level Rise Allowance + Maximum High Tide + Total Storm surge (designated storm)
>
> FCRP = DFL + Estimated Wave Effect
>
> FCL = FCRP + Freeboard

Recommended allowance for future sea level rise is based on the lifetime of the infrastructure under consideration, an absolute rate of sea level rise of 1 cm/year and local crustal movement (subsidence/uplift).

Recommended allowance for maximum high tide is to use the Higher High Water Level Large Tide – a value corresponding to the largest tide expected on average each year.

Recommended allowance for storm surge is based on the storm surge level corresponding to the 0.2% AEP (500-year return period) plus an allowance for local wind setup.

Recommended wave effect depends on the application. For coastal dikes, the recommended effect is either the 2% exceedance wave runup (the runup level exceeded by only 2% of waves) during the design storm, or the crest height required to restrict overtopping to acceptable levels during the design storm.

Freeboard accounts for uncertainties in the flood hazard analysis including future climate change, future sea level rise, future changes in site conditions, uncertainties in the statistical modelling, and uncertainties in the available measured and modelled data. Recommended freeboard is at least 0.6 m (a value historically used in BC for flood management).

The Provincial Guidelines are a straightforward and generally applicable method for specifying the ocean conditions which can be used to calculate the DFL, FCRP and FCL, but, the method is not without drawbacks. One issue with this approach is that it relies on the concept of a 'design storm', but does not provide a clear methodology for specifying this storm. The tendency is for the user of the Guidelines to specify design storm conditions (local wind-setup, wave effect) based on the projected extremes of these parameters (as was done in Moffatt & Nichol (2012)). This can result in a design storm which could not possibly occur or very improbable given the driving weather and geographic conditions.

Another serious issue is that, though the return period of the combined tide and storm surge event can be roughly estimated (Ausenco Sandwell, 2011a, Appendix D), the AEP of the combined event (tide, storm surge, wind setup, wave effect) is unclear. In many cases, it may be that the relative ease of applying the Provincial Guidelines outweighs the cost of any added conservatism that the method may introduce. In areas where the risk associated with coastal flooding is high and the costs associated with mitigation are high, we argue that a method which specifies the AEP of the design ocean conditions more precisely is justified.

4.3.2 The Continuous Simulation Approach (Joint Probability)

Unlike the Atlantic Coast, physical processes driving extreme waves and water level on the Pacific Coast are only weakly correlated. In the continuous simulation approach, all factors affecting water level are hind-cast over a long period (50+ years). The benefit of this approach is that there is no need to assign a probability to each of the individual water level components; the joint probability of the individual sea level components is inherently contained within the hind-cast. Extreme value analysis can be performed directly on the response of interest, in this case the static water level. This approach is suggested by FEMA for coastal flood hazard analysis on the Pacific Coast (FEMA, 2005b). Because the continuous simulation approach accounts for the joint probability of individual sea level components, it may be generally referred to as a 'joint probability approach'.

In this work, a combination of measured and modelled data has been used to synthesize a hind-cast of water levels and waves in Burrard Inlet over the past 50 years (1963-2012). This hind-cast includes, tides, storm surge (PDO/ENSO), local wind setup and wave setup. The hind-cast of the individual components was then used to calculate the response of interest, the static water level, in the surf zone of four shoreline zones around the City.

The total water level was not used as the target response because the wave runup (a component of total water level) is a metric specific to situations where waves are breaking at the shoreline. With several of the sea level rise scenarios under consideration the City is significantly inundated, making a wave effect metric based on the wave amplitude more appropriate. Given the significant variations in wave amplitude that can occur in shallow water, it was required to model wave propagation over land.

Extreme value analysis of the static water level hind-cast was then used to calculate the magnitude of the 0.2% and 0.01% AEP (500- and 10,000-year return periods) events in each of the shoreline zones. These values were used to synthesize boundary conditions for a hydrodynamic model that transferred the response to the overland areas. The maximum static water level calculated by this model is equivalent to the Designated Flood Level (DFL) discussed in the previous section.

The dynamic part of the wave effect for the extreme events was then calculated using a sophisticated two-dimensional spectral wave model. Water levels for the wave model were set to the maximum elevation calculated by the flood model. Wave and wind boundary conditions were set corresponding to similar storms observed in the hind-cast. The wave effect was set corresponding to the wave amplitude exceeded by only 2% of waves in the sea-state.

For each of the extreme events considered, summing the maximum inundation elevation and the wave effect produces an elevation equivalent to the Flood Construction Reference Plane (FCRP) discussed in the previous Section. Like the Provincial Guideline approach, the addition of a freeboard is used to account for uncertainties in the analysis and the results is the Flood Construction Level.

4.4 Available Background Data

Measured data was compiled and used in the synthesis of the coastal hind-cast, and are summarized in **Table 3**.

Table 3. Summary of measured data used in coastal hind-cast.

Data Type	Location	Duration	Source
Tidal			
Harmonic Constituents - Derived constituents	Victoria	n/a	CHS[5]
Harmonic Constituents - Derived constituents	Point Atkinson	n/a	CHS
Harmonic Constituents - Derived constituents	Vancouver	n/a	CHS
Hourly Measurements - Water Level	Point Atkinson	1914-2013	DFO[6]
Hourly Measurements - Water Level	Vancouver	1919-2013	DFO
Hourly Measurements - Water Level	Victoria	1910-2013	DFO
Meteorological			
Hourly Measurements - Wind Speed, Run, Direction	Entrance Island	1969-2013	EC[7]

[5] Canadian Hydrographic Service
[6] Fisheries and Oceans Canada
[7] Environment Canada

Data Type	Location	Duration	Source
Hourly Measurements - Wind Speed, Run, Direction	Sisters Island	1975-2013	EC
Hourly Measurements - Wind Speed, Run, Direction	Ballenas Island	1966-2013	EC
Hourly Measurements - Wind Speed, Run, Direction	Comox A	1953-2013	EC
Hourly Measurements - Wind Speed, Direction	Halibut Bank	1992-2013	DFO
Wave			
Hourly Measurements - Sig Wave Height, Peak Period	Halibut Bank	1992-2013	DFO
Hourly Measurements - Sig Wave Height, Peak Period	Point Grey	1978-1979	DFO
Hourly Measurements - Sig Wave Height, Peak Period	West Vancouver	1972-1974	DFO
Bathymetry			
10 ensemble multibeam data - Depth	Pt Atkinson to 2nd Narrows (full coverage)	n/a	CHS
Single beam tracks - Depth	Pt Atkinson to 2nd Narrows shoreline	n/a	CHS

Table 3 shows only the data utilized in the coastal hind-cast. For a complete summary of data collected in the course of the work, see Table A.2 of **Annex A**.

4.5 COASTAL HIND-CAST

A combination of measured and modelled data has been used to synthesize a hind-cast of water levels and waves in Burrard Inlet over the past 50 years (1963-2012). This hind-cast accounts for waves, tides, storm surge, local wind setup and wave setup. Effects of the PDO and ENSO are contained within the storm surge data.

Tidal water levels were calculated based on harmonic constituents available from the Canadian Hydrographic Service. External storm surge was calculated as the difference between the calculated tidal water level and the measured water level at Point Atkinson. Wave conditions were hind-cast using a 2D unstructured (flexible mesh) wave model. Wind setup and wave setup were found to be the smallest contributors to the total water level; both were calculated using a 1D parametric model.

A schematic of the modelling approach is provided in **Figure 6**. Tide and storm surge data are provided as a still water level to the wave model. Measured wind data are used to drive the wave model and the wind setup model. Using the wave model results at the 10 m bathymetric contour, the static wave setup was calculated using a 1D parametric model. The tidal water level, external surge wave setup and wind setup were then summed to arrive at a total water level. All components were calculated at 1 hour intervals throughout the hind-cast period.

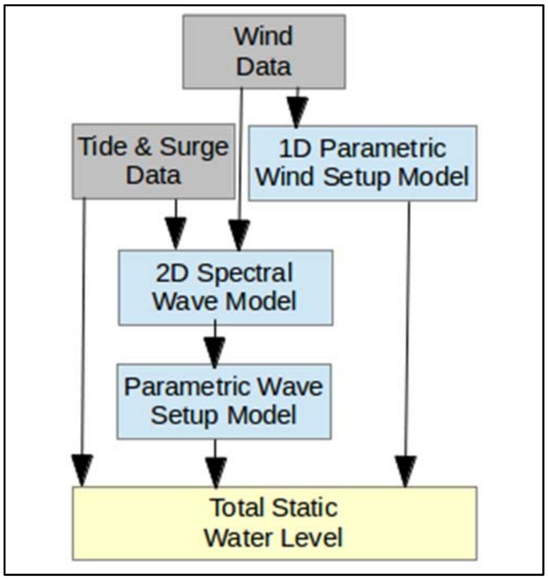

Figure 6. Schematic of coastal hind-cast approach.

The City shoreline was divided into four coastal zones based on the prevailing coastal and shoreline conditions. These zones are:

- Zone 1, Kits Point to Point Grey
- Zone 2, False Creek
- Zone 3, First Beach to Lions Gate Bridge
- Zone 4, Lions Gate Bridge to Second Narrows Bridge.

Static water levels in the surf zone of each of these zones were hind-cast individually using methods discussed in the following sub-sections.

4.5.1 Tidal Water Levels

Tides are a deterministic process resulting from the gravitational interaction of the sun, the moon and the earth and may be accurately described by a set of harmonic constituents (each consisting of amplitude and phase). The tides may be predicted by summing the sinusoids resulting from each of the harmonic constituents.

Initial hydrodynamic modeling of tides indicated low spatial variability of tidal water level within the Burrard Inlet. The tidal water levels within English Bay are spatially consistent within about 10 cm, and so may be represented accurately by the tidal elevation at the Point Atkinson tide gauge. The tidal water levels within the Inner Harbour are also spatially consistent within about 10 cm, so may be accurately represented by the tidal water level at the Vancouver Harbour tide gauge.

Tides were calculated using constituents obtained from the Canadian Hydrographic Service and the T_tide tidal analysis and prediction software (Pawlowicz et al., 2002). A comparison of tide heights at each station over a particular period are shown below in **Figure 7**. HHWLT at the Point Atkinson and Vancouver tide gauges are 2.0 and 1.9 m GD respectively.

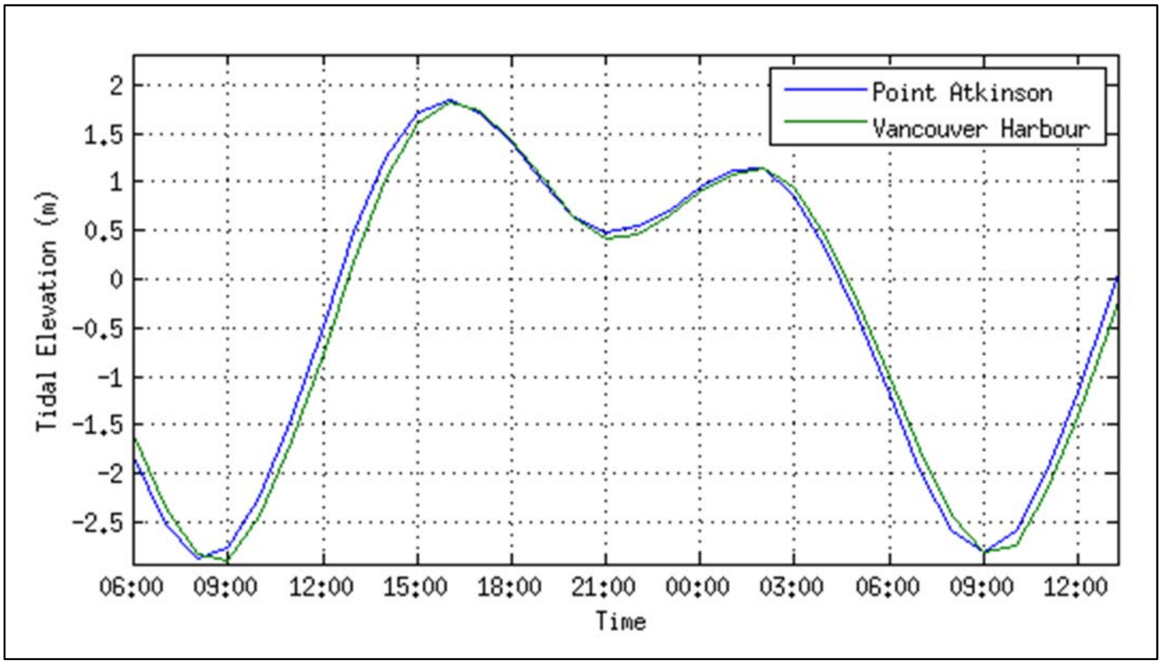

Figure 7. Tidal elevation (m GD) at Point Atkinson and Vancouver Harbour during a spring tide.

4.5.2 STORM SURGE

Storm surge accounts for atmospheric effects on water elevation as well as the response of the Strait of Georgia to water level variations in the Pacific Ocean (which propagate through the Juan de Fuca Strait).

Tide gauges are typically setup to filter the effect of waves; additionally, they are often located where the effects of local wind setup are small. Consequently, surge can be estimated as the tidal residual at most tide stations. The tidal residual is the difference between the measured water elevation and the elevation predicted by the tidal constituents.

Previous analysis of the tidal residual at ten tide stations within the Strait of Juan de Fuca and Strait of Georgia have indicated that external storm surge has strong spatial consistency throughout the region. **Figure 8** shows the tidal residual at Point Atkinson and Vancouver for a large event in March 1999.

In the coastal hind-cast, external storm surge was represented as spatially uniform. The hind-cast time-series was calculated based on the tidal residual at the Point Atkinson tide gauge and corrected for relative sea level rise to the year 2010 using the RSLR rates of Mazzotti et al. (2008). In this calculation method, the storm surge component also includes the effects of the PDO and ENSO.

Extensive quality assurance was performed on the Point Atkinson dataset to ensure that erroneous measurements were not interpreted as storm surge events. All 50 years of tidal residual was visually compared to the tidal residual from four nearby stations. Where the Point Atkinson data was found erroneous or missing, it was replaced with residual data from Vancouver Harbour or Victoria.

The largest RSLR corrected external storm surge event found in the hind-cast period (1963-2012) is 1.04 m.

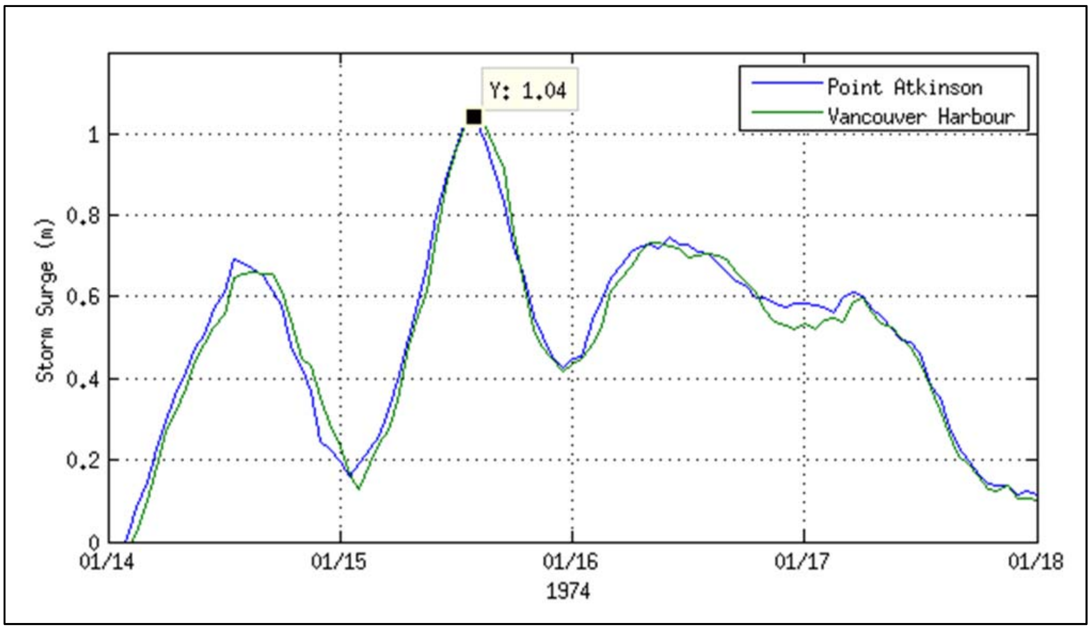

Figure 8. Tidal residual calculated at Point Atkinson and Vancouver Harbour.

4.5.3 WINDS

A combination of wind measurements from different stations were used to create a composite wind data-set representative of conditions over the Strait of Georgia with full temporal coverage of the hind-cast period of 1963-2012. An example is shown in **Figure 9**. These stations included: the Halibut Bank Weather Buoy, the Entrance Island Lightstation, Ballenas Island Lightstation, Sisters Island Lightstation and the Comox Airport. Each of these data-sets was scaled to a consistent measurement height (10 m) and averaging period (1 hour) using the Frøya wind profile (Det Norske

Veritas, 2010). For some stations, additional scaling was applied to account for local funnelling or sheltering of winds.

Comparison of wind data from the Vancouver International Airport to wind data from the Halibut Bank Buoy indicated that the Vancouver Airport measurements did not well-represent the wind over the Strait of Georgia, and therefore, were not included in the composite data set.

The largest wind speed in the composite wind data-set from the north-west (the wind direction to which the City is most vulnerable) is 21 m/s (76 km/hr) (hourly average). There was little correlation found between wind velocity and storm surge.

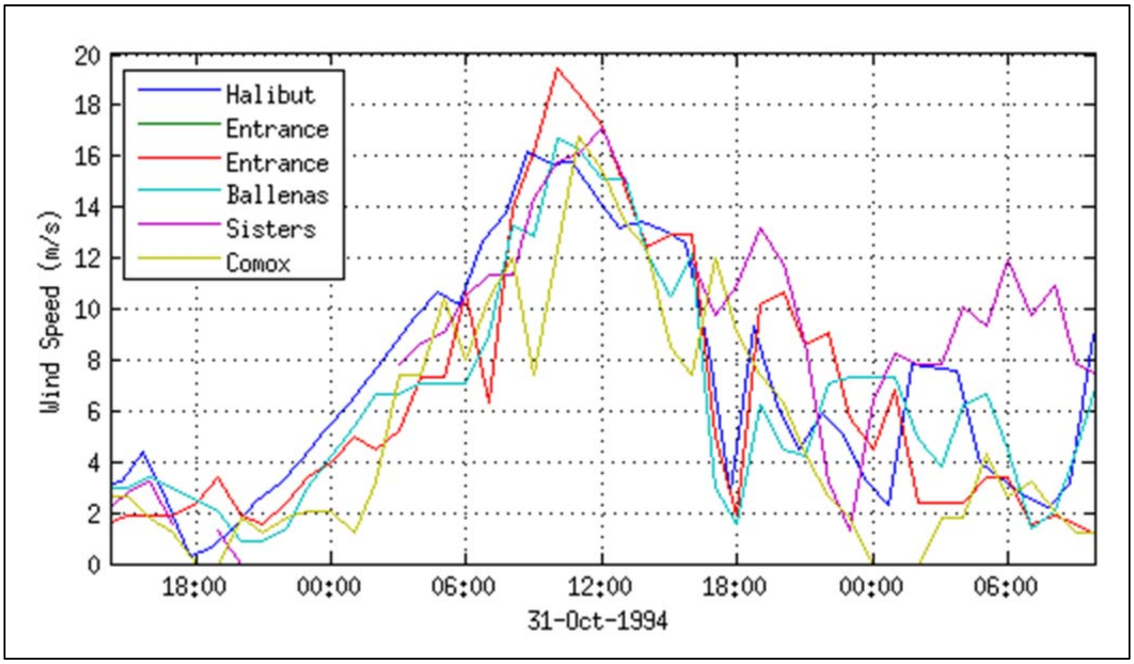

Figure 9. Wind speeds measured at various stations on October 21, 1994. Wind speeds have been scaled to 10 m height and 1 hour averaging duration.

4.5.4 LOCAL WIND SETUP

Wind setup is a fluctuation in water level resulting from shear stress by onshore wind over the water surface. Wind setup is largest where the wind blows over long stretches of shallow water.

Wind setup was initially investigated with a 2D hydrodynamic model of Burrard Inlet using the RiCOM software (Walters et al., 2009). The model was forced by winds from the Halibut Bank Weather Buoy and run with a still water level corresponding to low tide. Runs at high tide were also performed but resulted in smaller wind setup. A model run for the year of 2010 revealed that most reaches within the City saw a maximum wind setup less than 5 cm. Only False Creek experienced any significant wind setup with a maximum value of about 9 cm.

Though the wind setup in False Creek is non-negligible, it may be represented efficiently and to an acceptable degree of accuracy using a 1D model (Kamphuis, 2010). The 1D model uses wind velocity and the idealized geometric configuration of the inlet as inputs. For the entire year of 2010, the correlation between the 1D and 2D models at the head of False Creek is 99% with a bias less than 1 mm.

Using the 1D model, wind setup was calculated in False Creek over the hind-cast period of 1963-2012. The largest wind setup found in the 50 year hind-cast is 11 cm.

4.5.5 WAVE MODELLING

Waves in the Strait of Georgia are generated by local winds. To include waves in the coastal hind-cast a computational wave model was developed of the Strait of Georgia using the industry standard SWAN wave modelling software (Booij et al., 1999). The computational grid for this model was created using shoreline and bathymetric data obtained from the Canadian Hydrographic Service. The computational grid and bathymetry are shown in **Figure 10** and **Figure 11**. Grid resolution varies from 5 km far from Burrard Inlet to 10 m in the False Creek area. The entire Strait of Georgia is included to enable full wave generation potential.

The model is forced by the composite local wind data-set described in **Section 4.5.3**. Water levels were varied based on the tides and external surge at Point Atkinson. The model was validated to wave measurements at the Halibut Bank Weather Buoy as well as two older short-term wave buoy deployments at Point Grey and West Vancouver (see **Table 3**). The validation statistics for each wave buoy are given in **Table 4**. Note that quality assurance has not been performed on the measured buoy data.

The validation to the Halibut Bank Buoy, the newest and longest running of the buoys, is very good. Validation to the Point Grey and West Vancouver buoys is acceptable, but somewhat problematic. Part of the problems with these buoys is that they were located in very shallow water (<10 m) and in relatively sheltered areas. Consequently, the waves at these locations were usually very small (on the order of 20 cm). The wave measurement buoys and the wave model all struggle to accurately capture these low energy waves. For the larger wave events that we are more interested in, the wave model shows better correlation with the buoy measurements.

New measurements of waves in English Bay and the Inner Harbour were completed for this project. Though these measurements were not available in time for model calibration, they were examined during the final stages of this project. Unfortunately, an issue with the wave sensor setup resulted in systematic errors in the wave measurements. With some in-depth data analysis, the modelled wave data was made equivalent to the measured data and enabled validation of the model through a number of moderate wave events. Complete details on the wave measurements and qualitative model validation are provided in **Annex C**.

The wave model was run on an hourly basis for the 50 year hind-cast period (1963-2012), which on a high performance workstation required 10 days to compute. Results were output along the 10 m depth contour within Burrard Inlet.

The largest waves occur around the most exposed areas: Spanish Banks and the East side of Stanley Park. The largest significant wave heights in the hind-cast are about 3 m at these exposed locations. At the entrance of False Creek, near Kitsilano Beach, the maximum significant wave height is about 2 m. Maximum significant wave height in the Inner Harbour is less than 1 m.

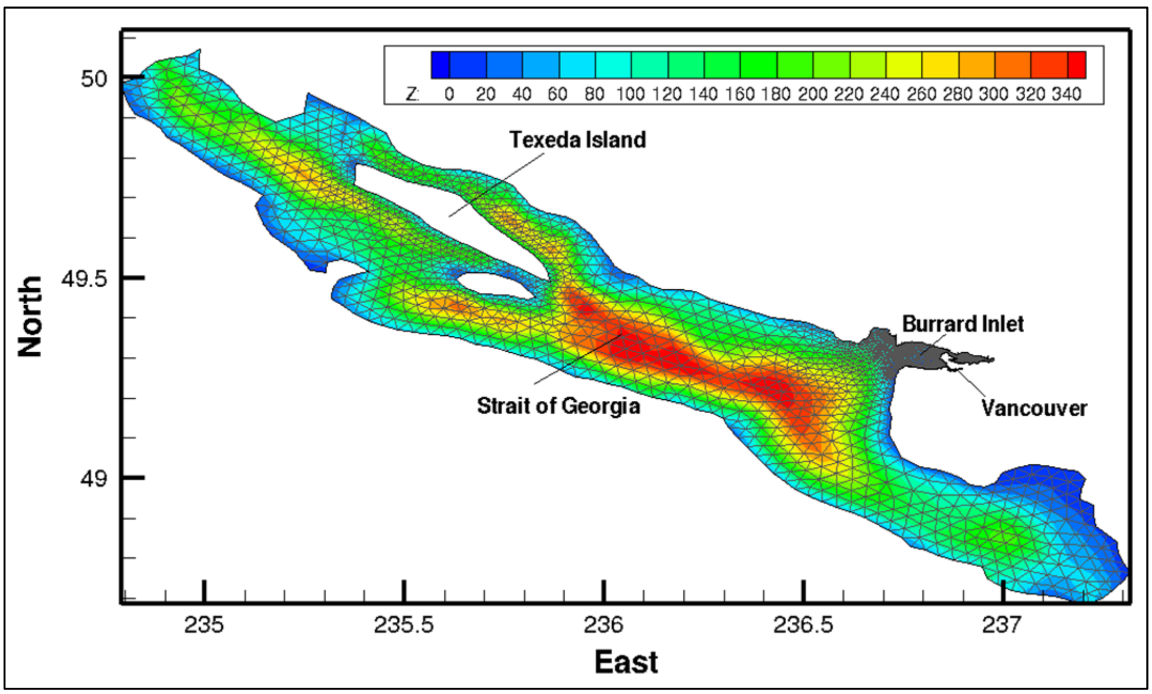

Figure 10. Wave model grid and colour contours of bathymetry (m).

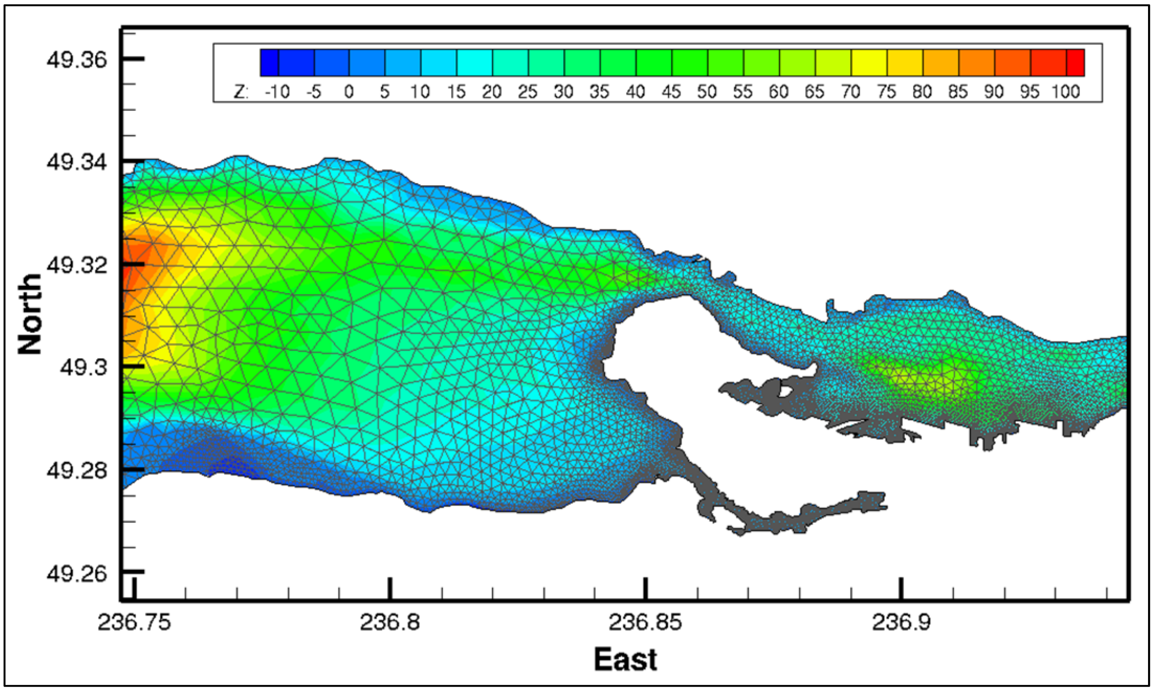

Figure 11. Wave model grid and colour contours of bathymetry, close up of Burrard Inlet.

Table 4. Validation statistics for the wave model.

Buoy	Deployment Period	Data Pairs	Bias (m)	RMS Error (m)	Correlation Coefficient
Halibut Bank	1992-2013	134486	0.05	0.15	0.90
Point Grey	1978-1979	5000	0.07	0.19	0.46
West Vancouver	1972-1974	2395	0.07	0.19	0.67

4.5.6 Wave Setup/Runup Calculations

Wave setup is an increase in water level shoreward of the wave breaking zone due to momentum transfer from breaking waves. Wave setup was calculated using the parametric formulation of the Direct Integration Method (FEMA, 2005a). This is the FEMA recommended method for calculating wave setup on the Pacific Coast.

Inputs to the parametric formulation of the Direct Integration Method (DIM) include the "deep water" significant wave height, peak period and spectral narrowness factor as well as the average beach slope. These parameters were sourced from the wave model output at the 10 m depth contour.

The wave setup varies significantly with wave exposure and beach type. The maximum wave setup in the hind-cast in Zones 1 to 4 are about 1 m, 0.3 m, 1 m and 0.4 m, respectively.

4.5.7 HIND-CAST SUMMARY

Tides, storm surge, wind, wave and wave setup data have all been assembled into the coastal hind-cast. **Figure 12** shows the hindcast components of water level for the December 2012 King Tide event. Tides are calculated using tidal harmonics based on water level measurements at Point Atkinson and Vancouver Harbour. HHWLT at Point Atkinson and Vancouver is 2.0 and 1.9 m GD respectively. External storm surge was calculated as the difference between the observed water level and the predicted tide at Point Atkinson. The largest RSLR corrected storm surge event in the hind-cast is 1.04 m. Local wind setup was found to be negligible through most of the City's reaches, with the notable exception of False Creek. Wind setup at the head of False Creek was estimated using a 1D model; the largest wind setup event in the hind-cast is 0.11 m. Waves were estimated using a 2D model of the Strait of Georgia. The model was validated to several wave buoys including the weather buoy at Halibut Bank. The largest waves in the hind-cast are about 3 m at Spanish Banks and the West shore of Stanley Park, 2 m at the entrance of False Creek near Kitsilano, and less than 1 m in Vancouver Harbour. Wave setup was calculated using a 1D model. Maximum wave setup observed in the hind-cast varies from 0.3-1.0 m depending on the location.

For Zone 1, the largest total water level event was 2.66 m on December 17, 2012. This event consisted of 1.94 m of tide, 0.46 m of external surge and 0.26 m of wave setup.

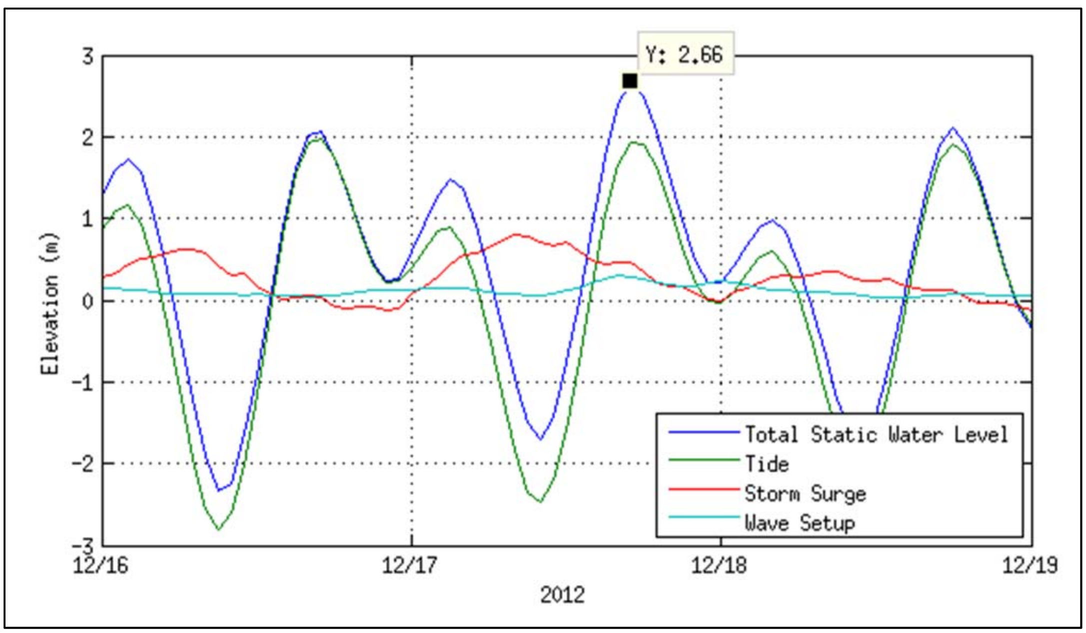

Figure 12. Hindcast components of water level for the December 2012 King Tide event.

4.6 OCEAN EXTREME LEVEL ESTIMATES

The data assembled in the coastal hind-cast is crucial to accurate projection and modelling of future flooding events. To project future flooding events, a statistical model was prepared using the Empirical Simulation Technique (EST) (Scheffner et al., 1999). Details on this technique are provided in **Annex B**.

This statistical model was used to project static water levels associated with return periods of interest to the City – 1:500 year and 1:10,000 year events – at each of the shoreline zones. These projections include tides, storm surge, and wind and wave setup at the existing shoreline and are given in **Table 5**.

Also given in **Table 5** are confidence limits for each estimate. The upper confidence limit is based on the 95% confidence interval of the EST analysis using a statistical tail calculated from the lower limit estimate of the storm tidal residual distribution (the lower limit results in larger tail). The lower confidence limit is based on the 5% confidence interval of the EST analysis using a statistical tail calculated from the upper limit estimate of the storm tidal residual distribution. Further details are provided in **Annex B**.

It should be noted that these estimates are based on a long, but statistically speaking, somewhat limited hind-cast record. The continuous simulation approach assumes that future events will be statistically similar in magnitude and frequency to past events. Implicit in this assumption is that event statistics are adequately represented by the hind-cast record and not significantly affected by climate change. This assumption is supported by best available evidence, but if future studies show that event statistics are not adequately represented by the hind-cast period or that climate change is significantly altering event statistics, then these extreme value estimates should be revisited.

Table 5. Total water level estimates at the shoreline of each zone for 500- and 10,000-year return period events.

	Shoreline water level (m GD) [mean estimate (lower limit, upper limit)]	
Zone	**1:500 yr**	**1:10,000 yr**
Zone 1 (Pt Grey – Kitsilano)	2.97 (2.92, 3.06)	3.18 (3.03, 3.50)
Zone 2 (False Creek)	2.94 (2.88 , 3.04)	3.11 (2.99, 3.59)
Zone 3 (English Bay – Stanley Park)	2.97 (2.91, 3.06)	3.18 (3.02, 3.55)
Zone 4 (Inner Harbour)	2.98 (2.94, 3.04)	3.16 (3.09, 3.46)

In consultation with the TAG, five scenarios were selected to be simulated and used to create flood maps. These scenarios combine a sea level rise with an extreme water level event of specific return period and are summarized in **Table 1**.

For each of the four shoreline zones, the water levels associated with the 500- and 10,000-year return period event are different. As a result, there are five different scenarios for each zone, for a total of 20 runs.

4.7 SYNTHESIS OF BOUNDARY CONDITIONS FOR THE OVERLAND FLOOD MODEL

The purpose of the coastal hind-cast and statistical modelling is to provide boundary conditions to the overland flooding and wave models. For these models to dynamically simulate each of the extreme events, more than just a static water level is required. An understanding of both the spatial and temporal variation of water level throughout a large event, and also the probable contribution from each component (tides, surge, wind, waves), is also needed.

4.7.1 WATER LEVEL

Each large water level event in the hind-cast was analyzed to determine the characteristic (mean) variation of water level in time and space. The characteristic temporal variation in water level at Zone 1 is given in **Figure 13**. The vertical axis gives the water level normalized by the peak value, and the horizontal axis is time in hours. The daily nature of the variation is due to the strong influence of tides on water level variations (even for large events). A time series of water levels to be used as boundary conditions to each overland flooding simulation was produced by multiplying the normalized temporal variation of the water level by the appropriate peak water level (**Table 5**) and adding the appropriate relative sea level rise (**Table 1**).

The spatial variation of water level was found to be small. This is a desirable outcome, as the very reason for dividing the shoreline into zones was to define areas experiencing similar conditions. Given the low spatial variability, the coastal boundary conditions for overland modelling of extreme events were specified as spatially constant.

Synthesis of the extreme event scenarios required the selection of appropriate contributions for tides, storm surge, and wave effect. Tides were set based on the King Tide event of December 17, 2012. The peak of this tide event is 1.94 m, a tide level which occurs on average only once every three years. The tidal residual (the non-tidal component of the water level) was specified by removing the tidal component from the computed static water level. For example, for Scenario 1 in Zone 1, the static water level is 2.97 m and the tidal residual is 2.97 - 1.94 = 1.03 m.

The peak values of sea level rise, high tide, tidal residual and static water level used in each of the overland modelling scenarios are provided in **Table 6**.

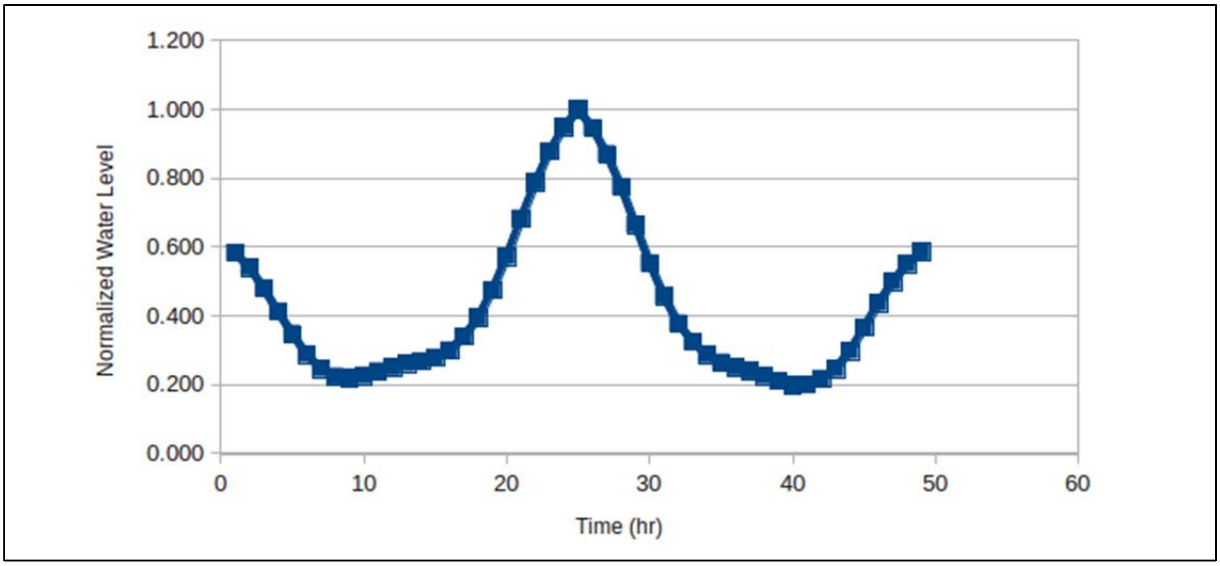

Figure 13. Characteristic temporal variation during a large event. Water level is normalized by the peak value of the event.

Table 6. Peak contributors to shoreline water level for each extreme event scenario for Zones 1 to 4.

Zone	Scenario	Sea Level Rise (m)	High Tide (m)	Tidal Residual (m)	Static Water Level (m GD)
1	1	0.0	1.94	1.03	2.97
1	2	0.6	1.94	1.03	3.57
1	3	1.0	1.94	1.03	3.97
1	4	1.0	1.94	1.24	4.18
1	5	2.0	1.94	1.24	5.18
2	1	0.0	1.94	1.00	2.94
2	2	0.6	1.94	1.00	3.54
2	3	1.0	1.94	1.00	3.94
2	4	1.0	1.94	1.17	4.11
2	5	2.0	1.94	1.24	5.18
3	1	0.0	1.94	1.03	2.97
3	2	0.6	1.94	1.03	3.57
3	3	1.0	1.94	1.03	3.97
3	4	1.0	1.94	1.24	4.18
3	5	2.0	1.94	1.24	5.18
4	1	0.0	1.94	1.04	2.98
4	2	0.6	1.94	1.04	3.58
4	3	1.0	1.94	1.04	3.98
4	4	1.0	1.94	1.22	4.16
4	5	2.0	1.94	1.22	5.16

4.7.2 WAVES

Under several of the extreme event scenarios, certain areas of the City experience significant inundation. In these cases, waves from coastal waters will propagate further inland past sea barriers such as the seawall. For this reason, the wave effect is an important component to incorporate into the calculation of Flood Construction Levels (FCL). Whereas large water level events typically do not coincide with large wave events, even moderate winds are capable of producing waves which pose a hazard to the City during flood conditions.

The wave conditions during each extreme event scenario were selected by examining the significant wave height concurrent to large tidal residual events in the hind-cast. The concurrent conditions were plotted and a linear relationship was fit to the data. This fitted linear relationship was then used to specify the offshore significant wave height for the extreme event scenario simulations. As an example, a plot of significant wave height and tidal residual for Zone 1 is provided in **Figure 14**. In Zone 1, for a tidal residual of 1.03 m, a significant wave height (Hs) of 0.5 m is estimated.

The limited fetch of the Strait of Georgia means that wave height and wave period are closely related. By correlating significant wave height (Hs) and peak period during independent events in the hind-cast, the following relationship was found for Zone 1 and Zone 2:

$$\text{Peak period} = 2.9H_s + 1.2$$

For a significant wave height of 0.5 m, a peak wave period of 2.7 seconds is expected.

For Zone 1, 2 and 3 the wave conditions were specified to correspond to a storm from the north-west. A storm with this heading has the greatest potential to cause large waves and run-up in these zones. Local geography restricts the propagation of waves from this heading such that the primary wave direction is always approximately 285 degrees.

Similar to wave direction, local wind fields during north-west storm events range in direction from 270 to 320 degrees. As the Strait of Georgia is a semi-enclosed basin, there is a strong correlation between wave height and wind speed. By correlating wind speeds with wave height (Hs) during independent north-west events in the hind-cast, the following relationship was found for Zone 1:

$$\text{Wind speed} = 7.7H_s + 4$$

For a significant wave height of 0.5 m, this yields a wind speed of 8 m/s.

Note that the relationship between tidal residual and wave height, wave height and period, wave height and wind speed are different for each of the shoreline zones. The boundary conditions used in each overland wave simulation are summarized in **Table 7**. See **Annex B** for more details.

Note that two sets of wave boundary conditions are given for each scenario in Zone 4. This is because this zone is vulnerable to winds and waves coming from both the north-west and the north-east. For systems coming from the north-west, the wind speed is typically less than for systems coming from the north-east and close to the wind speed values specified for the other zones.

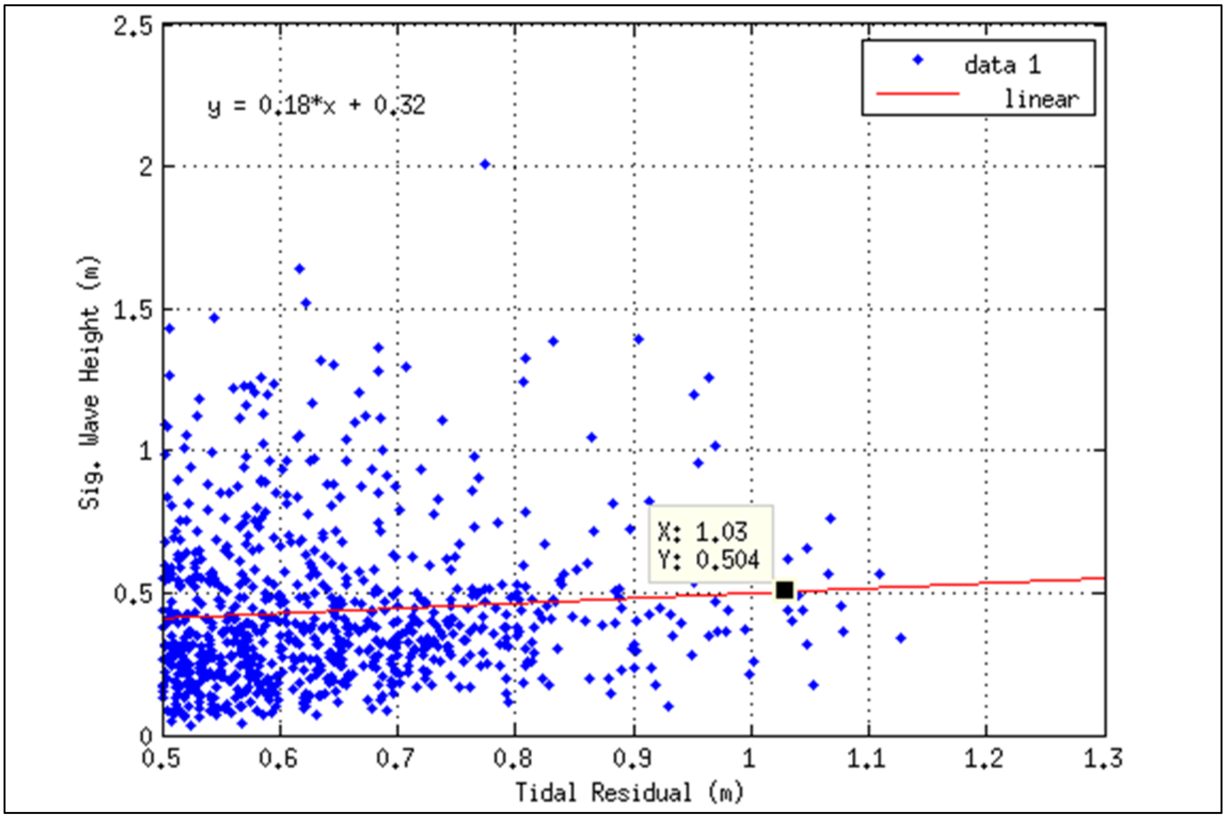

Figure 14. Hind-cast significant wave height during large tidal residual events.

Table 7. Overland wave model boundary conditions for each overland model run. Two sets of wave boundary conditions are given for each scenario in Zone 4.

Zone	Scenario	Tidal Residual (m)	Sig. Wave Height (m)	Peak Wave Period (s)	Primary Wave Dir'n (deg)	Wind Speed (m/s)	Wind Direction (deg)
1	1	1.03	0.51	2.7	295	7.9	295
1	2	1.03	0.51	2.7	295	7.9	295
1	3	1.03	0.51	2.7	295	7.9	295
1	4	1.24	0.54	2.8	295	8.2	295
1	5	1.24	0.54	2.8	295	8.2	295
2	1	1.00	0.54	2.8	295	7.8	295
2	2	1.00	0.54	2.8	295	7.8	295
2	3	1.00	0.54	2.8	295	7.8	295
2	4	1.17	0.57	2.9	295	8.0	295
2	5	1.17	0.57	2.9	295	8.0	295
3	1	1.03	0.60	3.0	275	7.8	275
3	2	1.03	0.60	3.0	275	7.8	275
3	3	1.03	0.60	3.0	275	7.8	275
3	4	1.24	0.64	3.1	275	8.0	275
3	5	1.24	0.64	3.1	275	8.0	275
4	1-1	1.04	0.38	2.4	65	12.0	100
4	2-1	1.04	0.38	2.4	65	12.0	100
4	3-1	1.04	0.38	2.4	65	12.0	100
4	4-1	1.22	0.43	2.5	65	13.0	100
4	5-1	1.22	0.43	2.5	65	13.0	100
4	1-2	1.04	0.38	2.4	320	9.9	310
4	2-2	1.04	0.38	2.4	320	9.9	310
4	3-2	1.04	0.38	2.4	320	9.9	310
4	4-2	1.22	0.43	2.5	320	10.9	310
4	5-2	1.22	0.43	2.5	320	10.9	310

4.8 Shoreline FCL Calculations

To facilitate comparison with past work, FCL values were calculated along the existing shorelines of the City.

4.8.1 Provincial Guideline Method

A 2012 study conducted by Moffatt & Nichol for the City investigated shoreline flood construction levels using the approach of the BC Provincial Guidelines (hereafter referred to as MN2012).

As described in **Section 4.3.1**, by the Provincial Guidelines the FCL is calculated as the sum of components corresponding to future sea level rise, high tide, storm surge, wind setup, wave effect and a freeboard. In the MN2012 work, the tidal component was selected corresponding to HHWLT. Storm surge, wave effect and wind setup were all specified individually based on a 200-year return period event. A number of different sea level rise scenarios were explored and wave effects were calculated at many different shoreline reaches throughout the City.

Table 8 shows the DFL and FCL calculated in each of the shoreline zones delineated in this work, as well as the component values which sum to give these values (See **Section 13** for definitions of DFL and FCL). For clarity, only SLR values of 1 m are shown. There are a range of wave effects and FCLs because each zone contains many reaches where MN2012 evaluated a range of design wave conditions.

Table 8. Shoreline FCLs calculated in MN2012.

Zone	SLR (m)	High Tide (m)	Storm Surge (m)	Wind Setup (m)	DFL (m GD)	Wave Effect (m)	Freeboard (m)	FCL (m GD)
1	1.0	2.0	1.3	0.2	4.5	1.0-2.0	0.6	6.1-7.1
2	1.0	2.0	1.3	0.2	4.5	1.6-3.0	0.6	6.7-8.1
3	1.0	2.0	1.3	0.2	4.5	1.0-5.0	0.6	6.1-10.1
4	1.0	2.0	1.3	0.2	4.5	0.5-0.8	0.6	5.6-5.9

4.8.2 Continuous Simulation Approach

In the continuous simulation approach the DFL is calculated directly by applying extreme value analysis to the hind-cast of static water level at each of the shoreline zones, then adding an allowance for sea level rise.

The wave effect is calculated based on typical wave conditions observed during high water events in the hind-cast. In this way, the AEP of the combined storm event is not significantly increased from the AEP associated with the DFL (see **Section 4.7.2**).

Here, the shoreline wave effect is given as the wave amplitude exceeded by only 2% of waves in the sea-state. This was calculated based on the significant wave height at the existing city shoreline (approximately 2 m GD contour) and generalized to a single value for each shoreline zone. Note that the wave effect immediately landward of the existing shoreline may be significantly less due to the effect of wave breaking, and will be affected by the presence of building or other infrastructure.

Table 9 shows the DFL and FCL calculated in each of the shoreline zones for the 0.01% AEP event (1:10,000 year event), as well as the component values which sum to give these values. Only SLR values of 1 m are shown. The wave effects in each shoreline zone were generalized so that only one wave effect value is given for each zone.

Table 9. Shoreline FCLs calculated in current study for 10,000-year event.

Zone	SLR (m)	Static Water Level (m GD)	DFL (m GD)	Wave Effect (m)	Freeboard (m)	FCL (m GD)
1	1.0	3.18	4.18	0.40	0.6	5.18
2	1.0	3.11	4.11	0.15	0.6	4.86
3	1.0	3.16	4.16	0.50	0.6	5.26
4	1.0	3.16	4.16	0.40	0.6	5.16

4.8.3 DISCUSSION

The shoreline FCL values calculated by MN2012 are much larger than the nominal value of 3.5 m used historically in the Province. There are a few reasons for this difference: 1) a SLR value of 1 m is added, 2) the probability associated with the DFL is considerably lower, and 3) a wave effect is added.

Further to the review of the Provincial Guideline method in **Section 4.3.1**, the AEP of the combined high tide and storm surge event can be roughly estimated at 0.01%. To these values MN2012 added a wind setup and wave effect allowance corresponding to the 0.5% AEP event for each of these components. If storm surge, wind setup and wave effect were not correlated this would result in a combined event with an AEP of $2.5(10^{-7})$%. In the Strait of Georgia storm surge, wind setup and wave effect are weakly correlated so that in reality the AEP of the combined event would be greater than $2.5(10^{-7})$%, but the example gives an indication of the extremely low probability associated with the FCL values in MN2012.

The shoreline FCL calculated in this current study are larger than those used historically in the Province, but less than those calculated in MN2012. Again, the reason these values are larger than the 3.5 m used historically is because of the addition of a SLR allowance, the decreased probability of the event associated with the DFL, and the addition of a wave effect.

The DFL values calculated in the current study and MN2012 are similar, only about 30 cm different. Most of this difference is due to the MN2012 calculations adding a wind setup allowance corresponding to a 0.5% AEP event.

The largest difference in the FCL calculations is due to differing wave effects. Where MN2012 calculated a wave effect based on an estimated 0.5% AEP wave event, the current study calculated the wave effect based on typical wave conditions during high water events observed in the hind-cast (see **Section 4.7.2**). With the current approach, the AEP of the combined storm event is not significantly altered from the AEP associated with the DFL. This agrees with the observation that the weather systems that produce large surge events in the Strait of Georgia typically do not produce winds capable of generating large waves at the City's shore.

5 HYDRAULIC MODELLING – BURRARD INLET

When modelling future coastal flood risk, an inundation model is typically used to simulate the potential flooding inland. To do this, an open boundary is established offshore and forced by a water level time series of extreme water levels with an associated probability of exceedance (return period). Correctly resolving the total water level in a coastal inundation model is crucial and has been documented by many as the greatest source of uncertainty in coastal inundation models. To address the spatial variability along the City's shoreline and to help find an appropriate balance between the mesh resolution and computation time, the study area was split into four overland zones.

Figure 15 shows the overland modelling area delimited into zones considered to be in hydraulic isolation from each other due to high ground or other constraining features. At the selected boundaries (blue lines in **Figure 15**), the interaction of flow between the zones is expected to be minimal or non-existent. Similarly, at the selected upland zone boundaries (red lines in **Figure 15**), there is limited or no interaction of flow between zones (this will be discussed in a later section). It is also assumed that the City would raise an East-West road for emergency response, thereby providing artificial upland boundaries between Zone 2 and Zone 4.

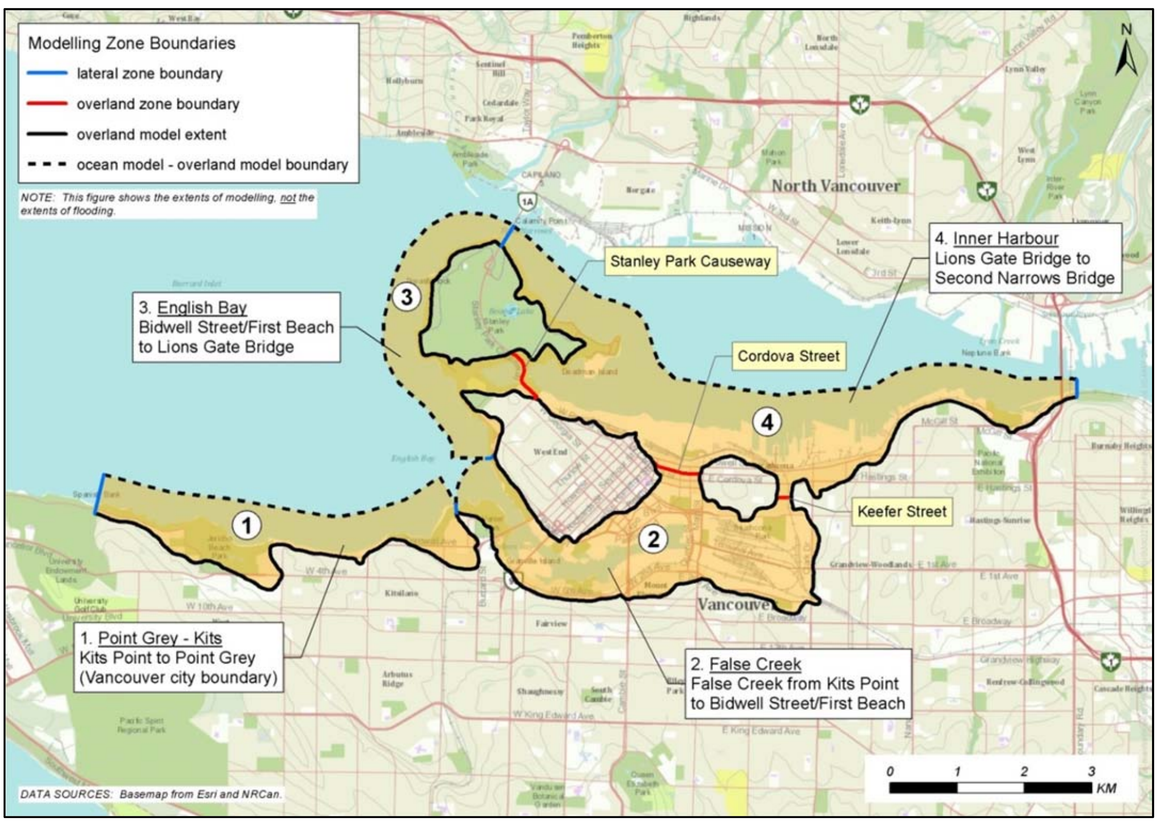

Figure 15. Flood modelling zones in Burrard Inlet.

5.1 Modelling Background

5.1.1 Software Selection

A two-dimensional (2D) overland flood model was developed using TELEMAC2D (Version 6.2), a suite of programs developed by Electricité de France and a consortium of users from around the world (www.opentelemac.org). TELEMAC is an integrated modelling tool for studying free-surface flows and related parameters, such as sediment movement. The TELEMAC algorithms are based on the finite-element method, and for hydrodynamic modelling, solve the St-Venant Equations. The TELEMAC system was selected as it (1) offers faster computational speed compared to other 2D hydrodynamic models, (2) its treatment of dry areas is robust which is important in tidal zones, and (3) it allows the option to adjust or add to the source code as required.

5.1.2 Modelling Urban Environments

In urban settings, flood flows are typically shallow and follow complex flow paths along roads, between buildings, and over topography that is highly variable. For these reasons, developing and evaluating an urban hydraulic model involves an order of magnitude increase in data and model resolution compared to that required for rural environments. Background information on the particularities of modelling urban environments is included in **Annex D**.

5.2 Model Development

5.2.1 Mesh Generation

The overland model mesh extents are shown in **Figure 16**. A detailed sub-mesh was generated for each of the four zones and was, in turn, incorporated in the larger mesh.

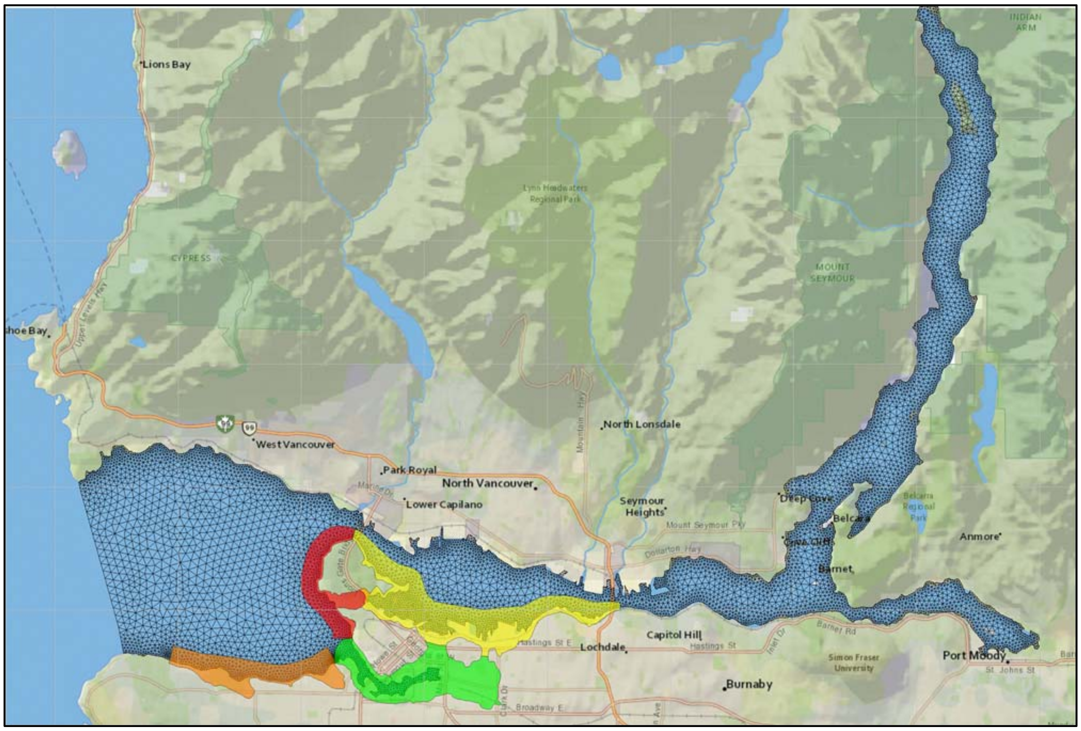

Figure 16. Overland model extents with detailed sub-mesh areas for each zone shown in different colours (Zone 1 = orange, Zone 2 = green, Zone 3 = red, Zone 4 = yellow).

For the generation of the four detailed sub-mesh, breaklines were added to guide the placement of nodes to ensure elements were aligned with the shoreline, edge of streets, edge of parking lots, and other topographic features. Buildings were removed from the mesh using building footprints provided by the City. Mesh elements inland were generated based on a node spacing specification of 5 m. This distance was selected as a compromise between the opposing requirements of maintaining reasonable computational times and providing a sufficiently detailed representation of the study area. A node spacing of 5 m corresponds to two elements over the average width of a street and one element over the mean building separation distance. Buildings with a separation distance of less than 5 m were merged together using a generalisation algorithm. A zoomed-in view of the Zone 2 mesh at Granville Island is shown in **Figure 17** to illustrate the level of detailed included in the mesh.

The stormwater system may provide some flood relief during the recession of the flood, but likely would have limited effect on the flood peak, and was not included in the model.

Additional details on the mesh generation process are provided in **Annex D**.

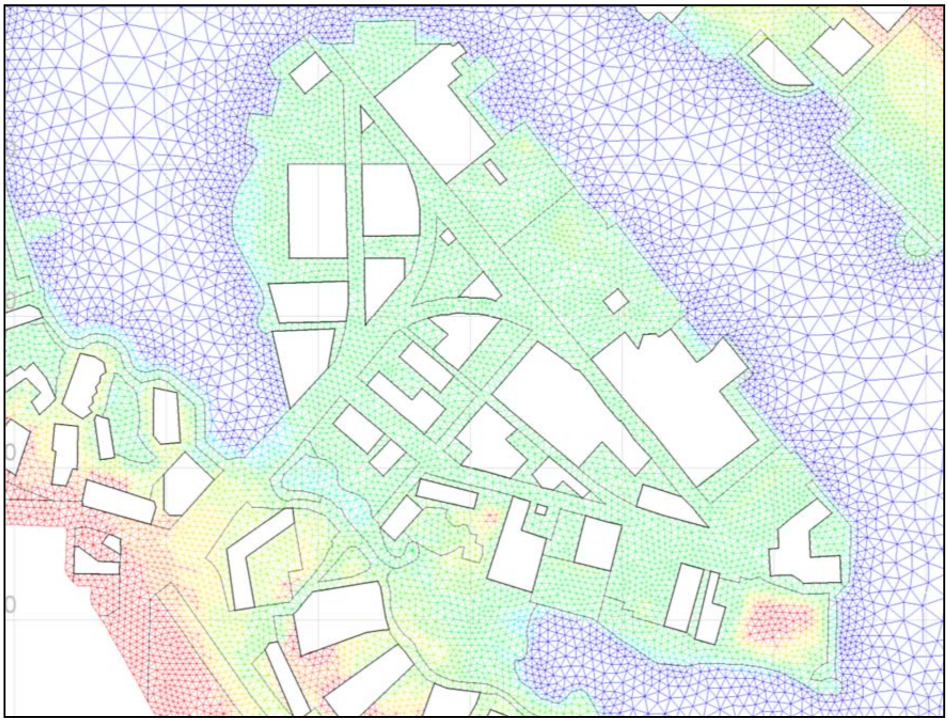

Figure 17. Zoomed-in view of Granville Island to show mesh detail.

5.2.2 TOPOGRAPHY AND BATHYMETRY

Ground and bed elevations were interpolated onto the mesh nodes from the following datasets:

- 2013 LiDAR at 0.5 m horizontal resolution
- Multi-beam soundings
- Single-beam soundings

Refer to **Annex D** for additional details.

5.2.3 ROUGHNESS COEFFICIENTS

Roughness coefficients (Manning's n value) represent the flow resistance due to various sources of energy loss. The model domain was classified into categories based on the 2011 land-use data and 2013 tree canopy data provided by the City. Additional details on the roughness values assigned to each category are provided in **Annex D**.

5.3 MODEL CALIBRATION AND VALIDATION

Calibration and validation are standard steps in the model development process. These steps consist of comparing observations from historic flood events with the model's ability to simulate those events. Unlike records of fluvial flooding, comprehensive data sets are rare for coastal flood events because these latter events tend to occur rapidly with little warning and most often in the winter. Potential sources of data on flood extents include ground and aerial photographs, newspapers with empirical evidence and first hand descriptions from witnesses. Water depths, wrack marks (debris or other temporary evidence left behind that record the location of the flood water) and measurements of flow velocity or flow rates are sources of hydraulic data.

With sufficient data, model parameters can be adjusted to achieve better agreement with observations (calibration) before validating the model by simulating a second independent event. This process provides confidence in the model's ability to predict other events of similar magnitude. Ideally, models should be verified against all the variables of interest: flood extent, water depth, velocity field, time of occurrence, duration of event.

5.3.1 DECEMBER 2012 KING TIDE

The recent King Tide that occurred on December 17, 2012 was well-documented with inundation extents captured in numerous photos and videos along the City's shoreline. Flood extents were identified on the photos and videos and digitized in GIS. Locations of photos and videos are shown in **Figure 18**.

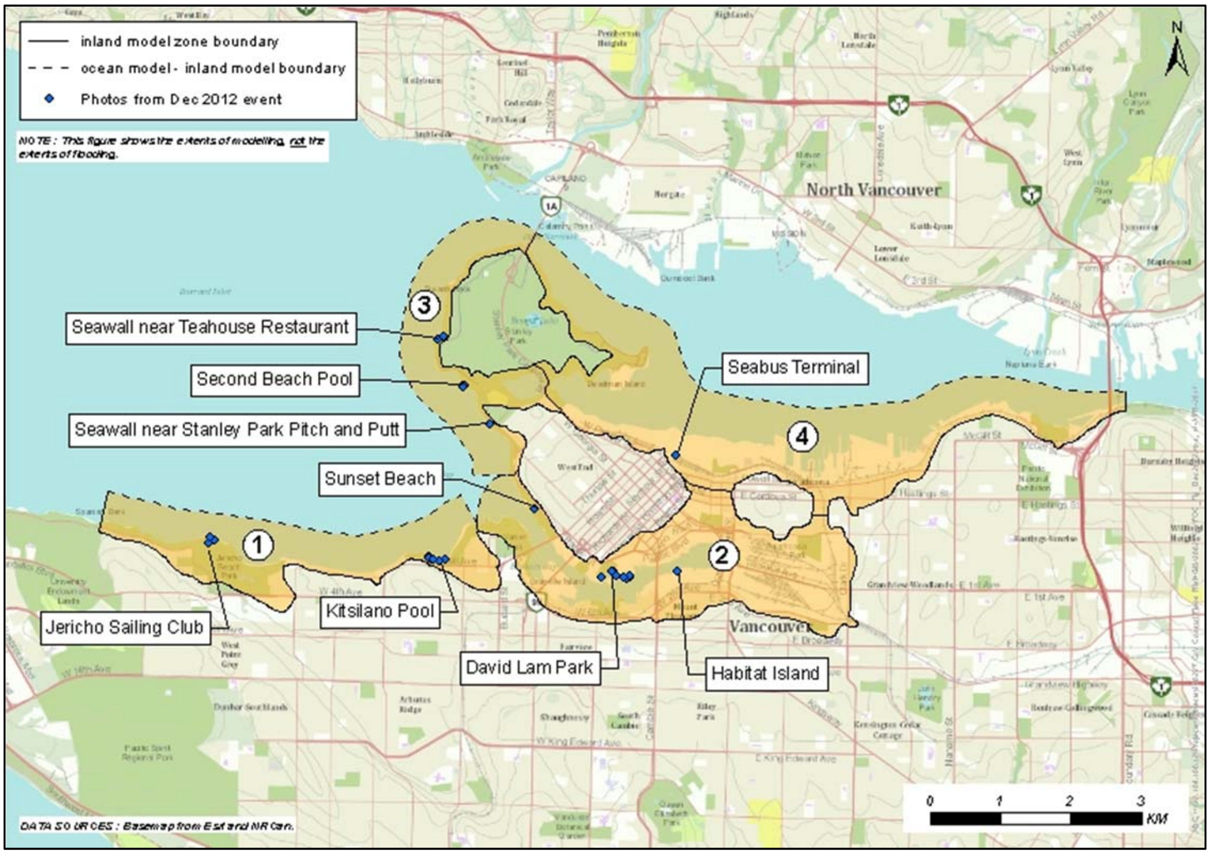

Figure 18. Locations of photos showing flood extents on December 17, 2012.

The flood extents simulated by the model for the December 2012 tides were then compared with the observed flood extents.

Figure 19 shows an example comparison between the modelled and observed flood extents. The light blue line corresponds to the observed flood extents while the area shaded in darker blue corresponds to the modelled flood extents. All other comparison figures are included in **Annex D**.

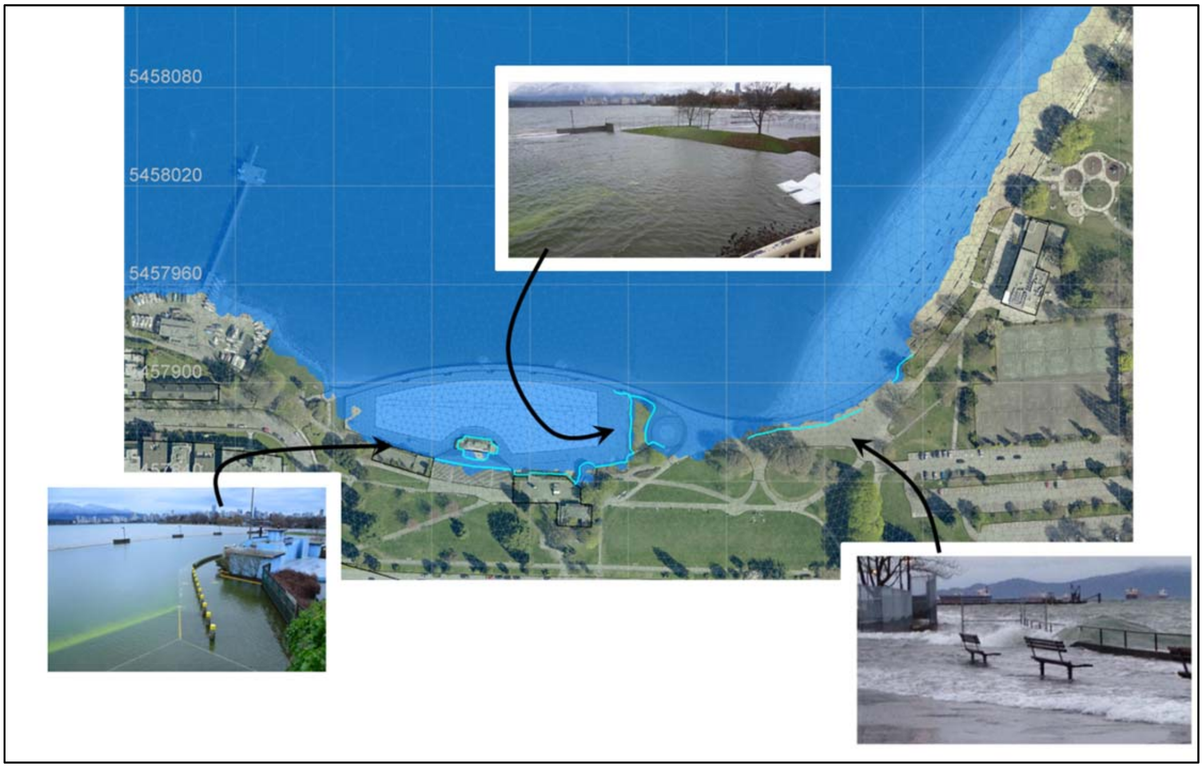

Figure 19. Comparison of observed and simulated flood extents at Kitsilano Pool and Beach for December 17, 2012.

In general, the comparisons showed good agreement between modelled and observed flood extents. **Table 10** summarises the agreement for the locations where data was available.

Table 10. Summary of model's ability to simulate the December 2012 flood extents.

Location	Zone	Agreement
Kitsilano Beach	1	Excellent
Kitsilano Pool	1	Excellent
Jericho Sailing Club	1	Poor
West of Jericho Sailing Club	1	Poor
David Lam Park	2	Good
Sunset Beach	2	Good
Habitat Island	2	Good
Seawall near Stanley Park Pitch and Putt	3	Fair
Second Beach Pool	3	Excellent
Seawall near Teahouse Restaurant in Stanley Park	3	Excellent
PMV parking lot near SeaBus terminal	4	Poor

At Jericho Sailing Club, the agreement is not as good as other areas. The model shows larger inundation extents and roughly 0.2 m more water than what can be deduced from the photos of the event. There are two possible explanations for the difference in water levels. First, the large pier that extends out from the point was not included in the model and would likely provide some sheltering. Secondly, the water level applied at the Zone 1 boundary was constant and likely more representative of the wave setup conditions at Kitsilano Beach than those in the shallower waters near Jericho beach. Due to the flat topography, this relatively small difference in water levels results in significantly different flood extents at that location. The model predictions appear to be conservative in this area.

At the Port Metro Vancouver parking lot located near the SeaBus terminal, the model over-predicted the inundation extents. Ground elevations were surveyed by PMV along the edge of the parking lot at the shoreline. The surveyed ground elevations are 5 to 20 cm higher than the nearest points captured in the 2013 LiDAR. The difference between observed and modelled flood extents would seem to indicate that the LiDAR elevations are lower than reality, at least along the edge of the parking lot. Another possible explanation is that the photo does not show the flood extents corresponding to the peak water level (photo had no timestamp).

It should be emphasized that although the model showed a reasonable ability to simulate the December 17, 2012 flooding at most sites, the data available for comparison was limited. Furthermore, this event is of a much lower magnitude (peak water level of 2.66 m GD) than the five scenarios selected by the City. In December 2012, the flooding occurred within a narrow band with a maximum distance of 15 to 30 m from the shoreline. Hence, the validation process does not capture the model's ability to simulate the overland flooding (water depths and flow velocities) during future coastal flood events when water will flow along streets and between buildings. The model limitations and uncertainties should be considered when making decisions based on the model results and adoption of freeboard (factor of safety).

5.3.2 RECOMMENDATIONS FOR IMPROVED CALIBRATION

Documentation of future flood events will greatly assist with future calibration of the overland flood model and increase the accuracy of the modelling results. To aid in the proper calibration of a 2D model, measurements or observations of the following are required:

- Maximum inundation extents
- Flood propagation
- Water levels
- Flow velocity

Each type of observation is described in more detail in the sections below and various methods to collect the data are detailed. Due to the dynamic nature of coastal floods, it is crucial that the time of observation be noted for every photo or measurement, preferably in Pacific Standard Time (PST). General observations about other sources of water, obstructions, and presence and approx. height of waves are valuable pieces of information.

Measurements should be spread out spatially over the City of Vancouver's shoreline. Locations where flooding is likely to occur include:

- Spanish Banks Beach Park
- Jericho Sailing Club/Jericho Works Yard (Vancouver Parks Board)
- Jericho Beach near Point Grey Road
- Kitsilano Pool and Beach Park
- Granville Island
- Habitat Island/Park site at Southeast False Creek
- David Lam Park
- Sunset Beach
- Second Beach and Pool
- PMV parking lot near SeaBus terminal
- New Brighton Park

Inundation extents

Ideally, the inundation extents should be documented at the peak of the flood when the inundation extents are at a maximum. Flood extents can be documented at the peak of the flood by: 1) surveying the edge of water line or marking locations along the line with stakes and flagging tape (noting the time in PST on the flagging tape) to be surveyed later; 2) taking videos or photos to capture the flood extents. It is important that the time and locations of photos are noted. Photos can be taken from the ground, high points or the air; 3) after the flood, wrack marks and trash lines can be identified and surveyed. These usually consist of temporary features or objects (wood, grass, trash, etc.) that were transported onshore by flood waters and deposited at/or near the maximum flood extents as the water started to recede. There is a higher degree of uncertainty associated with wrack marks but they can still provide useful information if surveyed and photographed.

Flood propagation

Documentation of the propagation of the flood is very valuable for model calibration. This is easily documented by surveying the progression of the edge of water line during the flood event using either the stakes and flagging method described above or a series of photos. Again, the key piece of information to note is the time corresponding to the extents. Another option is to setup a webcam to take periodic photos to capture the progression of the flood water in an open area (such as a park or beach) where flooding is likely to occur.

Water Levels

The water level can be measured at a specific location using a staff gauge (time of reading must be noted) or continuous recorder gauge. Alternatively, the height of water (and corresponding time) can be manually marked on a vertical feature such as a post, building wall, etc. to be surveyed afterwards.

Flow Velocity

Estimates of flow velocities along streets or in other confined areas will help with the calibration of the model. Flow between buildings is unlikely to happen until peak tides reach levels higher than those observed in December 2012 but will most likely occur first at the Olympic Village and Granville Island.

Measuring velocity with a velocity meter can be expensive and is usually limited by the depth at which it can measure velocity. Two inexpensive and easy methods can be used to estimate the flow velocity in shallow areas. The first - and less accurate method - consists of noting the amount of time required for a small floating object (stick, leaf, etc.) to travel a known distance (of a least several meters). More than one measurement should be taken at a specific location and the time of the measurements (in PST) should also be noted. A second approach consists of using a metre stick to measure the velocity head. This method is relatively accurate in shallow or turbulent flow and is described in detail in Environment Canada's 2012 CABIN Wadeable Streams Field Manual. The method consists of measuring the water depth while the wide edge of the metre stick is parallel to the flow of water (D1) and again with the wide edge of the metre stick perpendicular to the flow of water (D2) (**Figure 20**). The metre stick must be strong enough not to bend against the current, be held perfectly straight, stay in exactly the same location when the ruler is turned, and fluctuating water levels will need to be averaged by the observer. Ideally, three to six paired measurements should be taken across a street or alley. The velocity (m/s) is calculated using the equation:

$$\text{Velocity} = (2g\Delta D)^{0.5}$$

where, $\Delta D = D2 - D1$ is the difference between the depth of the stagnation zone (D2) and the flowing water depth (D1), expressed in metres (note that measurements are probably recorded in centimetres, and if so, divide ΔD by 100); and g is acceleration due to gravity, or 9.81 m/s^2.

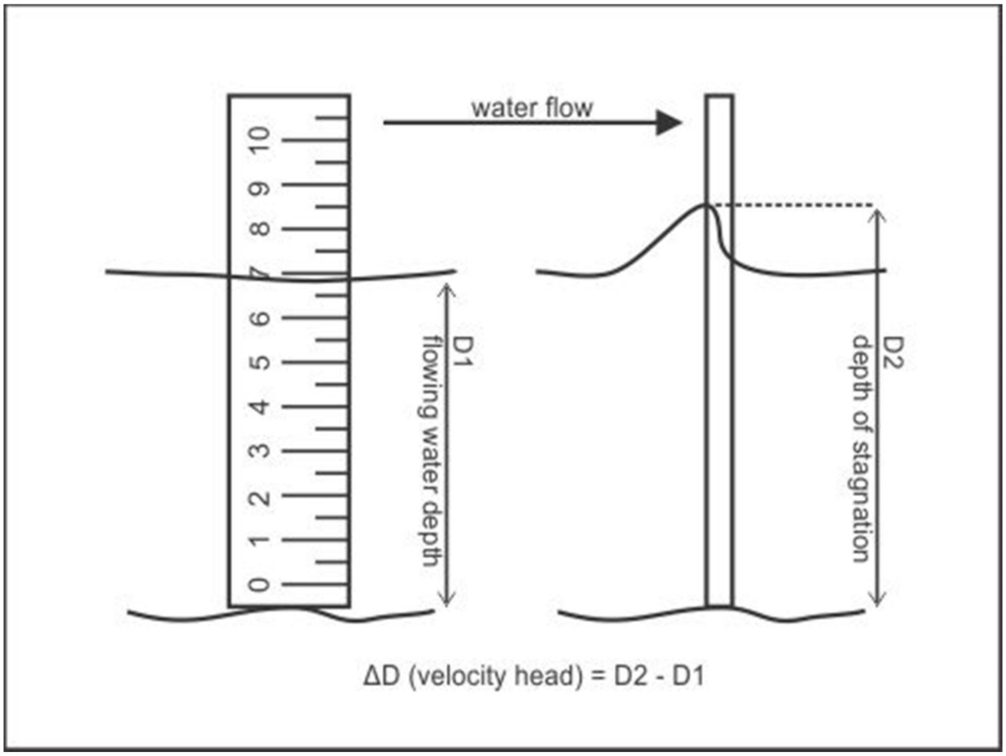

Figure 20. Using a metre-stick to measure velocity head.

5.4 MODEL SIMULATIONS

Following calibration, the overland flood model was used to simulate overland water levels. The five scenarios selected during the October 17, 2013 TAG meeting are summarised in **Table 1**. **Table 11** is a repeat of **Table 1** but also includes the modelled peak shoreline water level from the tidally-varying boundary condition provided from the coastal modelling analysis (**Figure 21**).

Table 11. Selected modelling scenarios and total water levels for Burrard Inlet.

Scenario	Year	SLR	Return Period	Method	Shoreline Water Level (m GD)
1	2013	0.0 m	1:500		2.97
2	2100	0.6 m	1:500	Joint	3.57
3	2100	1.0 m	1:500	Joint	3.97
4	2100	1.0 m	1:10,000	Joint	4.18
5	2200	2.0 m	1:10,000	Joint	5.18

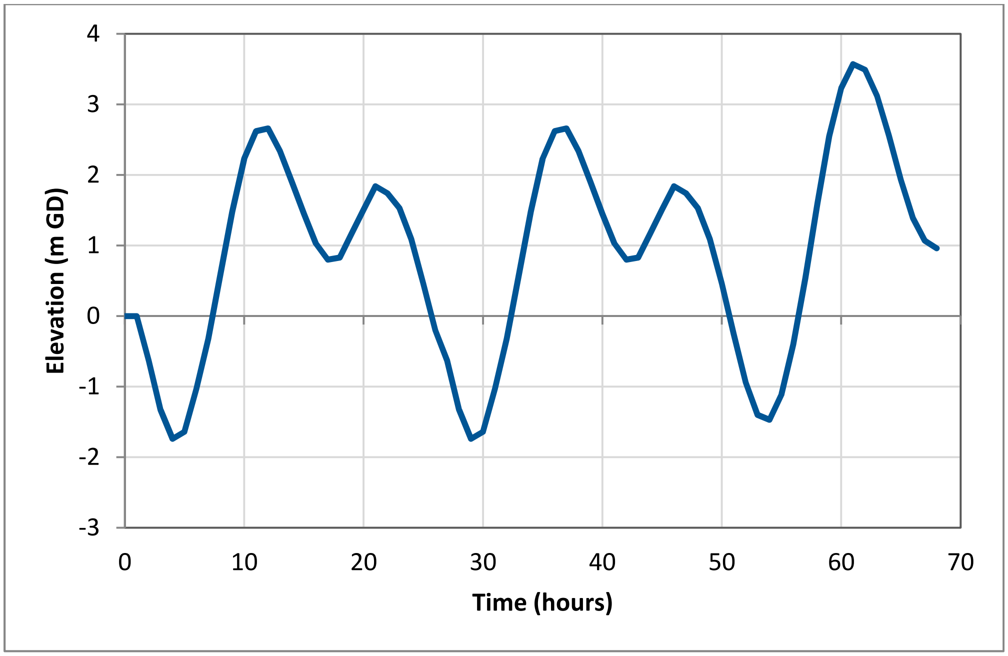

Figure 21. Sample tidal cycle used as forcing for overland model (Scenario 2).

The water level time series was imposed as boundary conditions to the overland flood model. The resulting simulated water depths in the flooded areas were post-processed in GIS and mapped.

5.4.1 FLOOD PROPAGATION

The propagation rate of overland flooding was analysed for Zones 1 and 2. In open areas, the flood wave generally travels at a speed of 0.2 m/s or less. In confined locations – between buildings, along streets, alleys and paths – the flood wave generally travels at speeds between 0.2 m/s and 0.6 m/s with speeds occasionally exceeding 1 m/s at some locations. No data are available to verify the modelled flow velocities. **Table 12** summarises the simulated time to reach maximum flood inundation extents for each of the scenarios. As the severity of the flooding scenario increases, the onset of flooding occurs earlier relative to the peak tide, and in some locations the flood wave continues to propagate inland after the tide offshore has started to recede.

Table 12. Simulated time to peak of flooding at Zone 1 and Zone 2 locations.

Scenario	Time to Peak (hr:mm)			
	Zone 1		Zone 2	
	Jericho	Kits Beach	Granville Island	Science World
1	2:50	2:00	N/A	N/A
2	2:20	2:30	1:20	1:10
3	2:30	3:15	1:50	1:45
4	2:45	4:00	2:10	2:30
5	3:30	4:30	3:10	4:20

5.5 SENSITIVITY ANALYSES

Without any observed data corresponding to flooding from peak tides greater than those documented in December 2012, it is not possible to evaluate the model's accuracy in predicting flooding for the five selected scenarios. In order to gauge the model's sensitivity to various input parameters and to help interpret the model results, sensitivity tests were performed. A summary of the results are included in this section while a complete description of the sensitivity analyses is included in **Annex D**.

5.5.1 BUILDING GENERALISATION

First, a sensitivity test was done to investigate the impact of generalizing buildings by merging those with a separation distance of less than 5 m. This test was done in the Kitsilano Beach area where merging rows of closely spaced houses was expected to have the greatest impact on the simulated flooding.

The modelled flood extents for Scenario 3 are almost identical except in the area where the merged rows of houses are parallel to the shoreline. The generalization of the buildings is only expected to have a local impact on the modelled flood extents in areas such as this one where closely spaced buildings are oriented perpendicular to the direction of flow. Generally, however, the peak water level used to establish the FCL would not be affected.

5.5.2 PEAK WATER LEVEL

The peak water level specified as a boundary condition in the model has an inherent degree of uncertainty associated with it. To verify the influence of this input on the modelled flooding, Scenario 3 was simulated with the peak water level adjusted by ± 0.1 m and ± 0.2 m.

The peak overland water levels were found to change by the same amount as the boundary adjustments. The flood extents in flat and/or gently sloping areas would be subject to variation, compared to steeper sloped areas. Flatter areas include Jericho Beach, Kitsilano Beach, Granville Island, False Creek flats, Lost Lagoon, Gastown, the Port Lands, and are most susceptible to changes in inundation extents as a result of changes in peak water levels.

5.5.3 Model Roughness Coefficients

Finally, tests were done to quantify the sensitivity of the model output to change in roughness values. Roughness parameters are used to represent the flow resistance due to various sources of energy loss. Difficulties arise when trying to characterise a specific land-use type as limited guidance is currently available for the selection of roughness coefficients for urban areas. The roughness values assigned to the mesh elements were adjusted by ± 20% and ± 40% to reflect the possible range of uncertainty. Varying the roughness parameter had limited effect on the modelled peak overland water levels and flood extents but did have a small impact on the modelled flow velocities and the time to peak.

One additional test was done where the roughness parameters corresponding to smoother surfaces ($n < 0.024$) were decreased by 20% and the roughness parameters of rougher surfaces ($n > 0.024$) were increased by 20%. This was done to investigate the effects of decreased energy losses along roads and higher energy losses on the adjacent properties. Results show virtually no change in modelled flood extents.

5.6 Model Limitations

The accuracy of simulated water levels and other output data is limited by the following:

- For mesh development, a generalization algorithm was used to merge closely spaced buildings (< 5 m apart) that would likely act as a single obstacle to the flow. Buildings were removed from the model mesh and building outlines represented by solid boundaries. No roughness value was assigned to these internal boundaries.
- Model roughness values were assigned based on typical land-use classes to represent the flow resistance due to various sources of energy loss. The accuracy of the model output is limited by the reliability of the water level data used for calibrating the model. Limited data was available at select locations but did not extend more than 15 m from the shoreline.
- The accuracy of model output is limited by the accuracy of the DEM. Data from LiDAR, surveyed in 2013, was used to create a Digital Elevation Model (DEM) for the City; the DEM surface was edited to remove buildings and temporary features. The DEM surface was also modified to include (1) the Powell Street Overpass, currently under construction, (2) modifications to Pacific Boulevard and Griffiths Way planned as part of the removal of the

Georgia Viaduct, (3) areas under bridges, and (4) pedestrian and road underpasses at Stanley Park Causeway east of Lost Lagoon.

- Changes to ground elevations, land use or buildings from those included in the model will affect the flood levels and render site-specific information obsolete. The modelled flood levels are based on ground conditions at the time of the surveys (and some anticipated future land use and building layouts).
- The model geometry was kept constant at all flows although variations (erosion, subsidence, or future constructions) may occur before or during a flood. Irregularities or blockages caused by fences, walls, hedges, vehicles, boats, or other barriers are difficult to characterize and were not represented in the model.
- The modelling does not take into account flood defences which may be in place now or in the future.
- The accuracy of the model boundary conditions and model parameters will affect the accuracy of the modelling results.
- Other sources of water (i.e. precipitation, groundwater, or sewer surcharge) and complex interactions between subsurface drainage networks and structures (i.e. SkyTrain infrastructure, underground parking, conduits, etc.) were not considered and can affect flood levels locally.

The model limitations and uncertainties should be considered when making decisions based on the model results. Some of the uncertainty in the modelling is accounted for by adding a freeboard value of 0.6 m when determining FCLs. Documentation of a larger flood event as per recommendations outlined in **Section 5.3.2** would enable a better calibration of the model and reduce some of the modelling uncertainty.

6 Hydraulic Modelling – Fraser River

Fraser River is the largest river on the west coast of Canada, draining approximately one-quarter of British Columbia. The source of the river is Mount Robson in the Rocky Mountains, and the river flows over 1,100 km to the sea. The gradient of the river decreases sharply downstream of Chilliwack, and its planform changes abruptly from a gravel-bed multi-channel to a sand-bed single channel that frequently divides around large islands. The river slope averages approximately 5 cm/km downstream of Mission and is tidally-affected at most times of the year. Important tributary inflows between Mission and New Westminster include the Stave, Alouette, Pitt and Coquitlam rivers.

The modern delta of the Fraser River begins near New Westminster, 35 km upstream from the sea. Immediately downstream, at the trifurcation, the river splits into three branches. The North Arm, which further divides into the Middle Arm near its mouth, borders the City where much of the channel is confined by training walls. The distribution of flow through this branched network of channels is governed by several variables including discharge, tide level, bathymetry and by local control from training structures. The North Arm carries approximately 10% of the total flow.

The snowmelt-generated freshet dominates the hydrology of the river. Flow typically rises in early April, peaks in the first weeks of June and then recedes through the summer. However, extreme water levels in the lower reaches are caused by the occurrence of high tides and storm surge in the winter season, rather than high discharges during the freshet (NHC, 2006; NHC, 2008). For the length of the study reach along the North Arm, the influence of the Fraser River winter discharge is insignificant compared to the tidal water levels.

6.1 MIKE11 Model

In 2006, NHC developed a MIKE11 model for Fraser River extending from just upstream of Mission to the Strait of Georgia. The Mission to Strait of Georgia model was developed based on 2005 bathymetry and LiDAR surveys (NHC, 2006). The model encompasses the North, Middle and South arms, including Canoe Passage, as well as Pitt River and Pitt Lake. The model was calibrated to the 2002 flood and verified to the freshet flows of 1999 and 1997. First developed for Fraser Basin Council in 2006, the Fraser River MIKE11 model was updated and extended for BC Ministry of Environment in 2008. NHC continues to support the Province in ongoing operation and maintenance of the model. NHC has an agreement with the Province to use the model for project purposes.

6.2 TIDES

Tide levels are used to set the downstream boundary condition for the numerical model. Design tide levels for the arms of the Fraser River were calculated using the Empirical Simulation Technique (EST; see **Section 4.6**). The levels at the mouth of the North Arm are summarized in **Table 13**.

Table 13. Selected modelling scenarios and total water levels for North Arm of the Fraser River.

Scenario	Year	SLR	Return Period	Method	Fraser North Arm Total Water Level (m GD)
1	2013	0.0 m	1:500		2.77
2	2100	0.6 m	1:500	Joint	3.37
3	2100	1.0 m	1:500	Joint	3.77
4	2100	1.0 m	1:10,000	Joint	3.91
5	2200	2.0 m	1:10,000	Joint	4.91

6.3 WINTER FLOOD DISCHARGES

The highest recorded daily winter flow reached 7,850 m^3/s at Mission on December 27, 1980 with an associated three-day flow average of 6,950 m^3/s (NHC, 2006). A review of the discharge records at Hope, Mission and the tributaries in between, showed that intense localized rainstorms in the Fraser Valley triggered this unusual winter flood event. In 2006, NHC completed a frequency analysis of maximum daily discharges in the winter season (October to February) using 36 years of data for Mission between 1965 and 2001. The 200-year winter discharges were also estimated for the four tributaries downstream of Mission. Values from those analyses are summarised in **Table 14**.

Table 14. Winter flood frequency analysis, for Fraser River tributaries and at Mission (NHC, 2006).

	Discharge (m^3/s)		
Return Period (years)	Tributaries Combined	Mission	Total
20	2,148	6,900	9,048
25	2,274	7,150	9,424
50	2,678	7,800	10,478
100	3,106	8,500	11,606
200	3,562	9,130	12,692

6.4 Sensitivity Analyses

Previous modelling completed in 2006 and 2008 established a design profile for the lower Fraser River. For the North Arm reach of the Fraser along the City boundary, winter tidal conditions result in water levels that exceed freshet levels. A Fraser River 200-year winter flood in combination with a 200-year ocean design condition (upper 95% confidence limit) was previously used to establish the winter design profile (NHC, 2008). Combining a 200-year winter flow with the winter design ocean level may seem overly conservative when considering the combined probability of both occurring simultaneously. However, results from sensitivity analyses (described below) show that in the study reach of the North Arm, the magnitude of the river discharge has almost no effect on the computed water levels during an extreme winter tide event.

As part of the sensitivity analysis, North Arm river profiles were computed for a Scenario 1 tide condition, with the 200-year, 100-year, and 20-year river flows. Relative to the 200-year flood, water levels were lower by a maximum 0.06 m and 0.14 m for the two smaller flow conditions. A 200-year winter flood was used for the assessment.

6.5 Model Simulations

The model was run for each of the five scenarios listed in **Table 13** combined with a 200-year winter flood flow. Flood depths and extents based on modelled water levels plus 0.6 m freeboard are shown on the Fraser River flood mapping presented in **Section 7**.

6.6 MODEL LIMITATIONS

NHC (2008) outlined the limitations of the Fraser River Hydraulic Model. The accuracy of water levels and other output data is limited by:

- The accuracy of the flow and water level data used for calibrating and validating the model.
- The range of high ocean tide levels to which the model was calibrated. Limited winter water level data was available for calibration. Tides from December 2002 were used when tides reached a maximum high water level of 2.42 m at Point Atkinson. For the extreme tides modelled under sea level rise conditions, assumptions must be made regarding the hydraulic roughness.
- Topographic changes that occur in the channel and on the floodplain over time in response to degradation/aggradation, new infrastructure such as bridges or dikes etc. Predicting river conditions nearly a century into the future is difficult. Dredging is assumed to continue, with removal volumes roughly equalling deposition. The local configuration of the channels and the trifurcation structure at New Westminster control the distribution of flow downstream of New Westminster. It was assumed that entrance conditions will remain unchanged.
- Changes in flow confinement due to potential breaching of dikes or overbank spills. The model assumes that existing dikes have been raised so that the flow is fully confined.
- A fixed-bed channel geometry, which does not reflect future channel geometry.

Use of the profile data provided assumes recognition of the above limitations. Background information on the modelling is provided in NHC's 2006 and 2008 reports.

7 Flooding Hazard Assessment

GIS was used to convert modelled flood levels from the overland flow model (TELEMAC2D) and the Fraser River model (MIKE11) to flood extents (boundaries) and depth using the City's 2013 LiDAR-based DEM.

7.1 Modelled Flood Extents and Depths

7.1.1 Modelled Flood Extents

For Burrard Inlet, modelled flood extents and flood levels including freeboard are shown on **Map Sets 1 and 7 to 11**, for 1 m of sea level rise in 2100 (with no associated storm event) and Scenarios 1 to 5, respectively. The freeboard expands the boundary beyond the modelled flood extents, more so where the ground is relatively flat. This areal difference is most pronounced in the eastern portion of Zone 2 where incorporating freeboard extends the boundary from Main Street to as far as Clark Drive to the east.

In the vicinity of Canada Place and the Vancouver Convention Centre, flooding may affect infrastructure that is located below elevated structures but not included in the model. Reconstruction of Stewart Street, on the Port lands between McLean Drive and Oxford Street, as an elevated road is currently in progress and is not represented in the model.

For the Fraser River, modelled flood extents including freeboard for Scenarios 1 to 5 are shown on **Map Sets 12 to 16**. Water level isolines are labelled on each map.

7.1.2 Modelled Flood Depths

For the Burrard Inlet, flood depths were calculated without freeboard and are presented for Scenarios 1 to 5 in **Map Sets 2 to 6**. For the Fraser River modelling areas, flood depths were calculated with freeboard and are presented for Scenarios 1 to 5 in **Map Sets 12 to 16**.

There is no international standard for mapping flood depths, although there are several national standards.[8] NHC has adapted the Japanese national standard (EXCIMAP, 2007) for depth categories with some modification for the flood maps. The modified categories are summarised in **Table 15**.

[8] The Canadian federal government (Public Safety Canada) awarded a contract for review of current flood mapping nationwide, and development of national flood mapping standards. This may result in recommendations for flood mapping categories, but was not completed in time for use in this project.

Table 15. Flood depth mapping standard adopted for the City of Vancouver study.

Depth	Description
0 to 50 cm	most houses are dry; walking in moving water or driving is potentially dangerous; basements and underground parking may be flooded, potentially causing evacuation
50 to 100 cm	water on ground floor; basements and underground parking flooded, potentially causing evacuation; electricity failed; vehicles are commonly carried off roadways
100 to 200 cm	ground floor flooded; residents evacuate
200 to 500 cm	first floor and often roof covered by water; residents evacuate
> 500 cm	first floor and often roof covered by water; residents evacuate

Depth map colours were also based on the Japanese Flood Control Division, River Bureau, Ministry of Land, Infrastructure and Transport (MLIT) standard, which uses shades of yellow-green-blue-purple (MLIT, 2005). These are easier to distinguish than several shades of blue. The colours will also be more distinguishable if the map is photocopied to greyscale, which can be common during an emergency event. Critical structures such as community centres, care facilities, public schools and fire stations were added for reference purposes.

7.2 Overland Wave Modelling

Under several of the extreme event scenarios, certain areas of the City will experience significant inundation. In these cases, waves will be able to propagate from coastal waters, past sea barriers such as the seawall, and travel further inland. The wave effect can be used to define areas that will be affected for planning purposes, or if appropriate, can be incorporated into the Flood Construction Levels (FCLs).

Variation in topography and obstacles such as headlands, the seawall and buildings can result in significant spatial variability of the wave field. The only way to adequately capture this variation is to use a computational wave model to simulate the propagation of waves over the flooded area. The same modelling software used in the coastal modelling was used again for the overland wave modelling.

Wave amplitude was mapped, rather than wave height, as the overland flood model is initialized with maximum water levels from the overland flood model[9]. Amplitude gives an indication of additional vertical extent of the water, and can be added to flood water levels and freeboard to calculate FCL.

FEMA (2014) notes that, "Recent post disaster assessments and wave tank research have shown that waves as small as 1.5 ft [0.45 m] can cause significant structural damage." In shallow water, waves become asymmetrical so that the wave amplitude is approximately equal to 70% of wave height. A wave height of 0.45 m corresponds to a wave amplitude of approximately 0.3 m.

7.2.1 Model Setup

The overland wave modelling was performed using the same industry standard SWAN wave modelling software used for coastal modelling of waves. In each shoreline zone, the wave model was run using the same unstructured computational mesh that was developed for the overland flood modelling.

The overland wave model is initialized with maximum water levels from the overland flood model and forced with coastal wave boundary conditions and local winds. Wave effects were only determined for Scenario 3 based on the wave conditions shown in **Table 7** and described in detail in **Annex B**.

7.2.2 Results

Figure 22 to **Figure 29** show details from the wave modelling results for Scenario 3. For Zones 1 to 3, wave effect was modelled and mapped for wave conditions corresponding to a storm from the northwest. This translates to waves coming from a direction of 295 degrees (relative to north) for upland modelling Zones 1 and 2, and 275 degrees for Zone 3. For Zone 4, storms from the north-east and north-west are possible and wave directions of 65 and 310 degrees were both considered likely. The mapping was based on the maximum amplitude from either of the conditions.

[9] Wave height is the vertical distance between peak and trough. A wave peak will be above mean water level, and a wave trough will be below mean water level. Wave amplitude is the vertical distance between wave peak and mean water level.

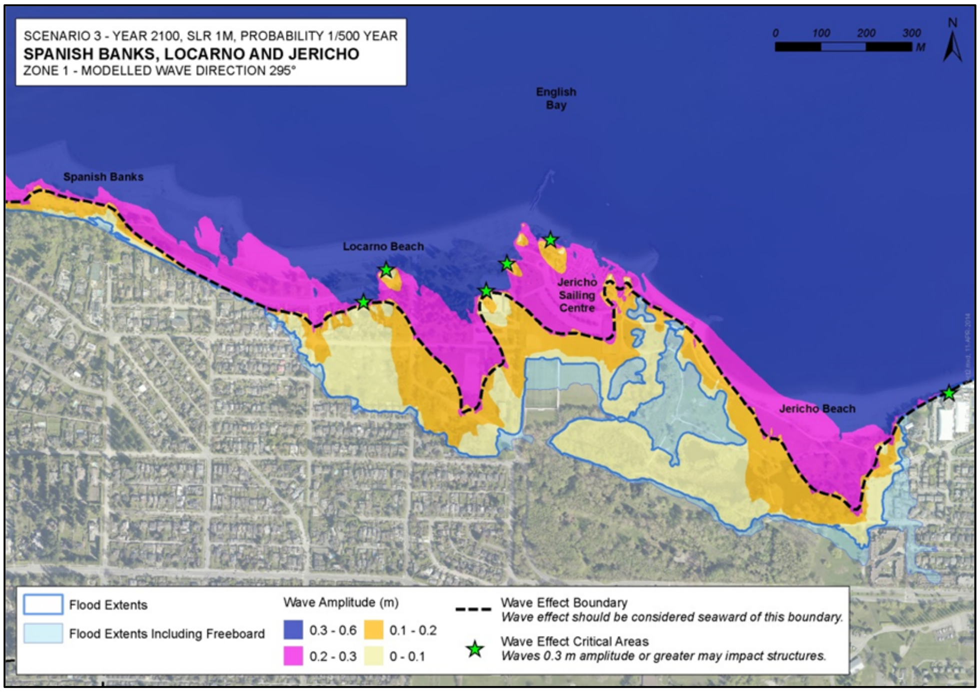

Figure 22. **Scenario 3 modelled wave effects – detail of Spanish Banks, Locarno and Jericho.**

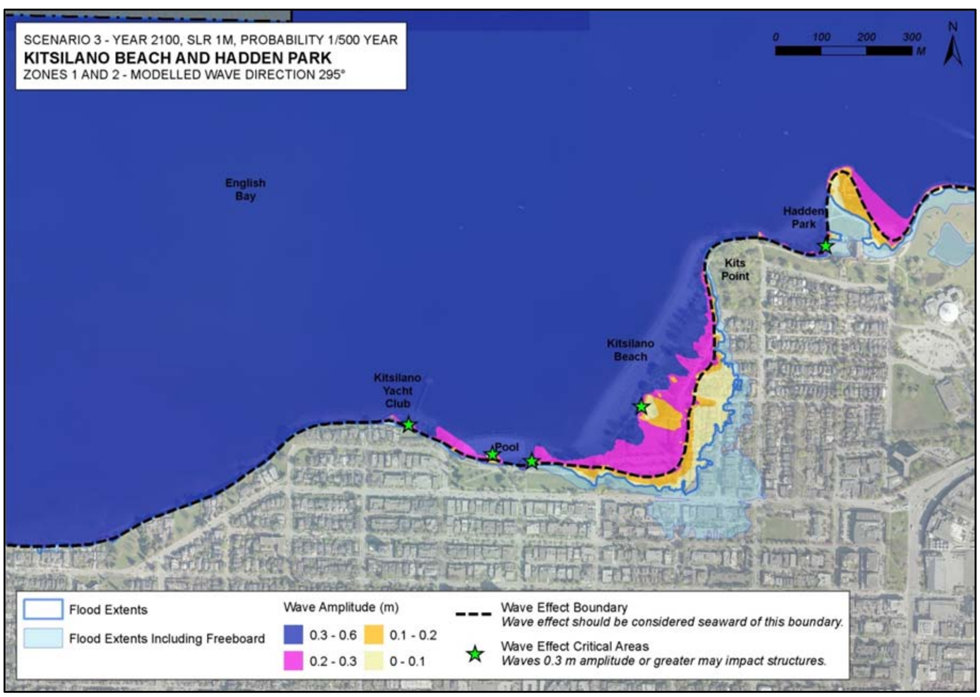

Figure 23. **Scenario 3 modelled wave effects – detail of Kitsilano Beach and Hadden Park.**

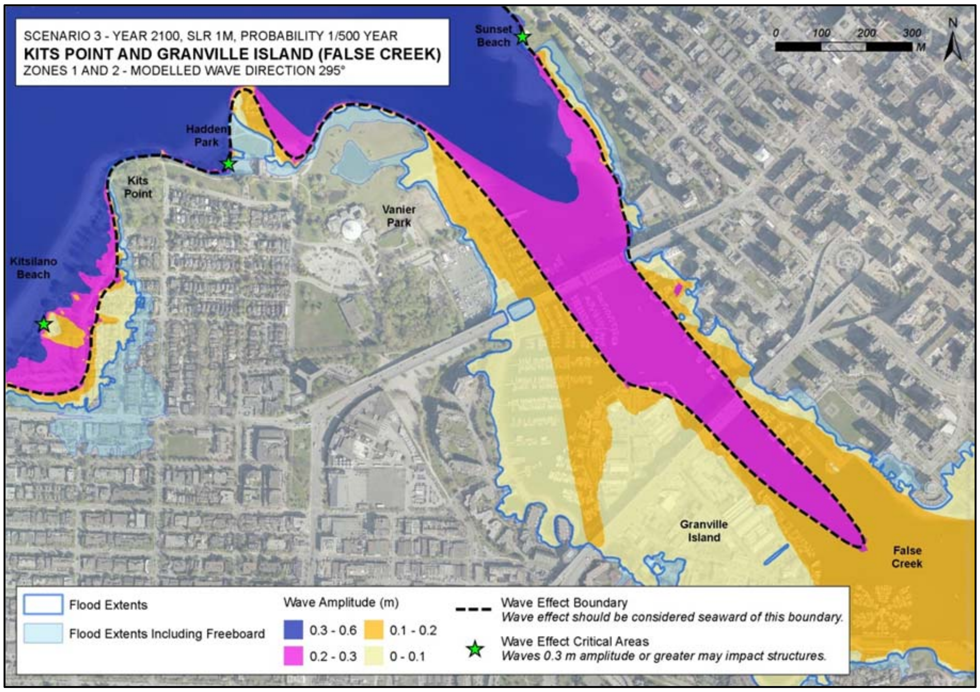

Figure 24. **Scenario 3 modelled wave effects – detail of Kits Point and Granville Island (False Creek).**

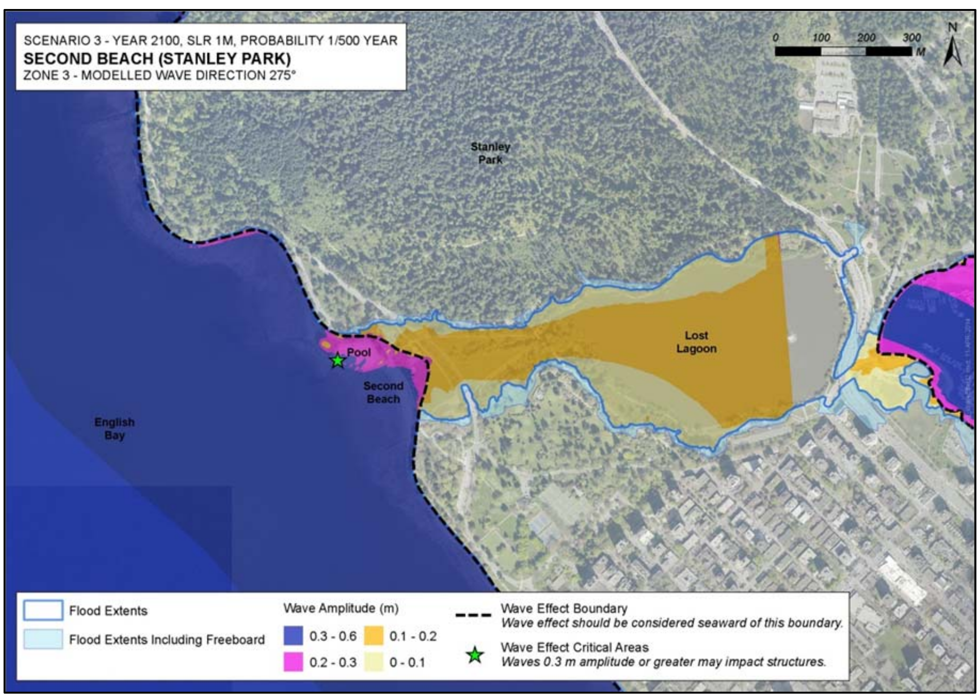

Figure 25. **Scenario 3 modelled wave effects – detail of Second Beach (Stanley Park).**

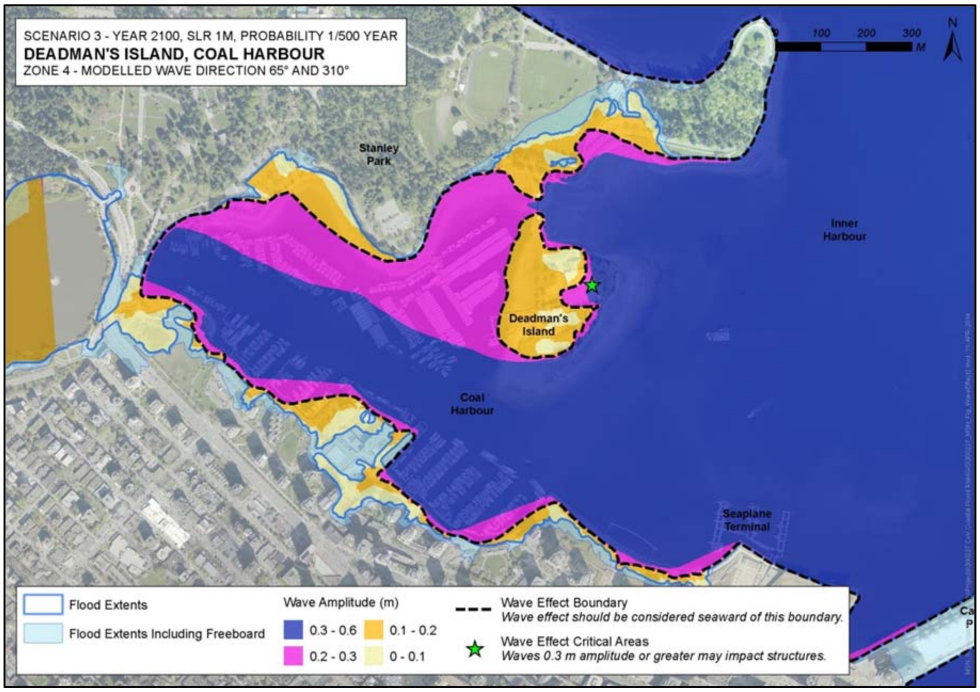

Figure 26. Scenario 3 modelled wave effects – detail of Deadman's Island, Coal Harbour.

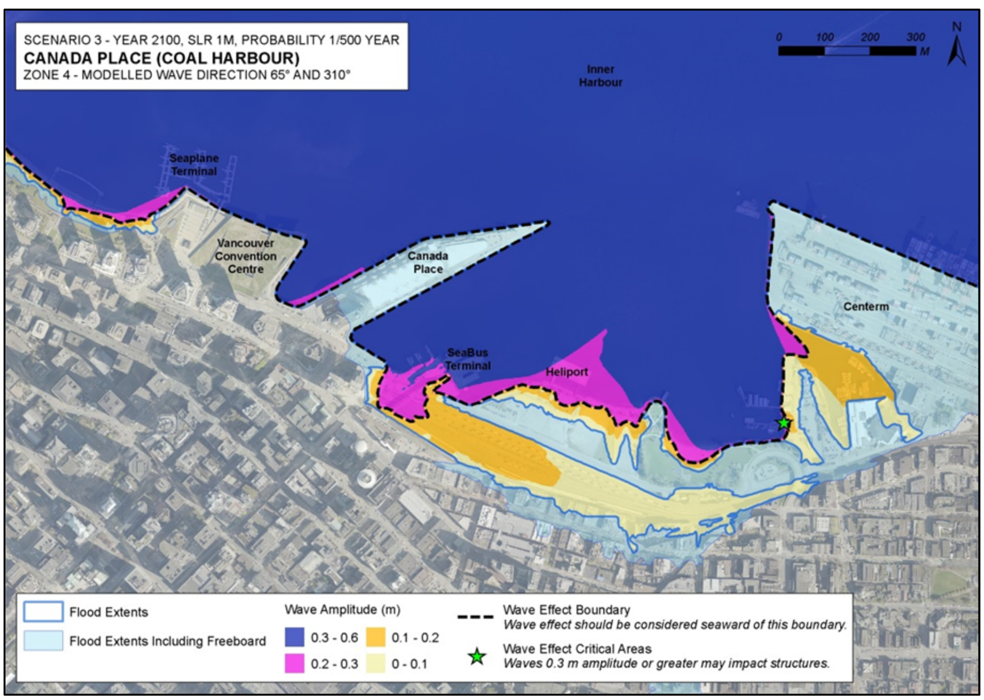

Figure 27. Scenario 3 modelled wave effects – detail of Canada Place (Coal Harbour).

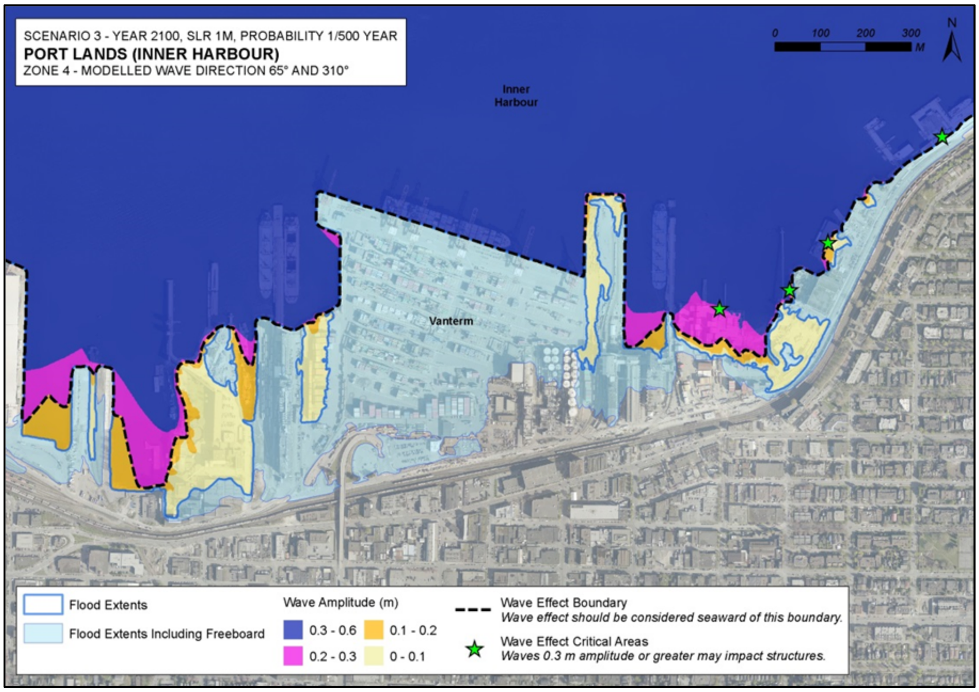

Figure 28. Scenario 3 modelled wave effects – detail of Port Lands (Inner Harbour).

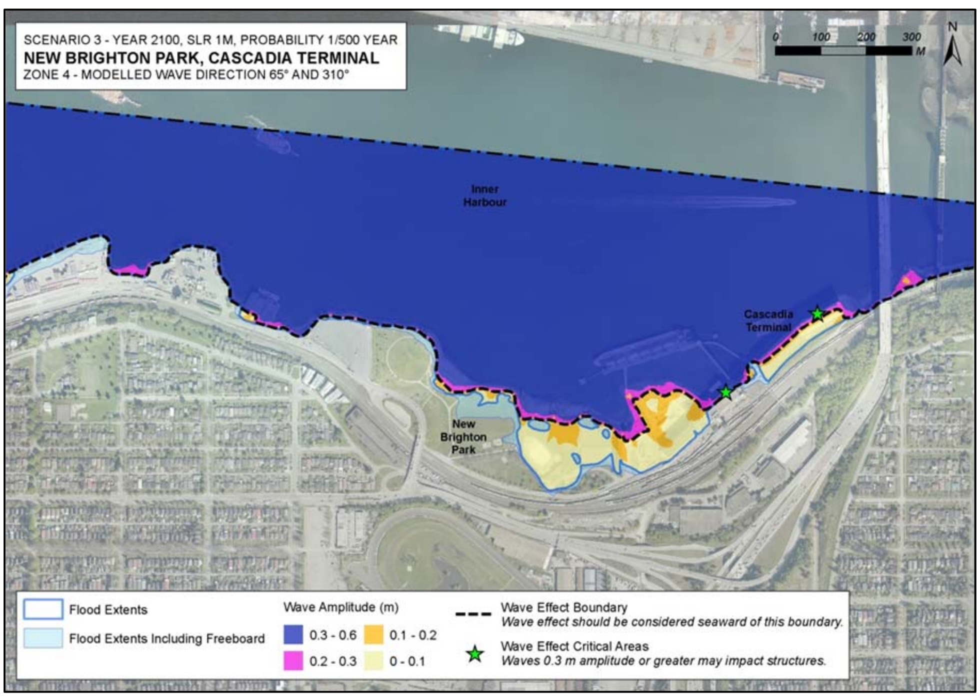

Figure 29. Scenario 3 modelled wave effects – detail of New Brighton Park, Cascadia Terminal.

A "Wave Effect Boundary" was defined as a smoothed representation of the 0.2 m wave effect contour, which captures the FEMA (2014) finding that waves with a height of 0.45 m (amplitude of 0.3 m) can cause damage. Wave effects apply seaward of this boundary, and need to be accounted for either by adding 0.3 m to the FCL, or by conducting a local wave effect study. No wave effect is necessary on the shoreward side of the boundary. Where a wave effect boundary crosses a building, the entire building is considered to be within the wave effect area.

Waves caused by other sources, such as boat traffic, tsunamis or landslides, were not considered in the model. Buildings were included in the wave model and have a sheltering effect; if building footprints change, the wave effect will be different from those mapped.

"Wave Effect Critical Areas" are also shown on the maps and identify locations where waves of 0.3 m amplitude (the boundary between dark blue and pink) could impact structures. Notable locations include homes at Jericho near NW Marine Drive and Sasamat Street; the Jericho Sailing Centre; Kits Pool and the Boathouse Restaurant at Kits Beach; Second Beach Pool; park facilities and structures in several locations; Deadman's Island at Stanley Park; and some Inner Harbour port facilities near PMV Centerm, east of PMV Vanterm, and at Cascadia Terminal.

Overall, wave effects in Zones 2 and 4 were found to be small. Wave effects were much more significant in Zone 1 and 3 due to their exposure to open water. The effect was greatest at the shoreline, where the significant wave height was upwards of 0.6 m and diminished with increasing distance inland.

7.3 FLOOD CONSTRUCTION LEVELS

Working with the TAG, a range of scenarios was developed that encompass possible future SLR conditions to 2200 combined with design storm events (**Table 1**). Modelled levels plus freeboard were obtained for each scenario for each zone within Burrard Inlet (**Table 16**) and locations along the North Arm of the Fraser River (**Table 17**). For Scenario 5 in Zone 2, water levels varied across the zone, and the range is indicated in **Table 16**. As per the Provincial Guidelines, the Flood Construction Level is to include a wave effect allowance, if present, in addition to the freeboard. As discussed in **Section 7.2.2**, a wave effect boundary was delineated, on the seaward side of which this allowance would be applied. The possible FCLs for wave zones and non-wave zones are also summarized in **Table 16** for each scenario.

Of these scenarios, it was necessary to select one scenario that would become the basis for setting Flood Construction Levels in the four flood hazard zones. Discussions with the TAG yielded two outcomes:

i. A sea level rise estimate of 1.0 m by 2100 was considered to be reasonable for planning for Vancouver given projected ground elevation changes and potential for ice sheet collapse; and

ii. The design flood on the Fraser River is the 1894 flood which has an approximate return period of 500 years (NHC, 2008). For consistency, and applicability to the City's degree of ocean exposure, the 1:500 year event was deemed appropriate for planning.

Scenario 3 meets both of these items and was chosen as the FCL-setting scenario.

The adopted Annual Exceedance Probability (AEP) is typically a function of the acceptable level of risk and ranges from the 1:20 to 1:2,500 year event in British Columbia (APEGBC, 2012). Adopting the 1:500 year event translates into the event having an 18% probability, on average, of occurring within a 100-year period as indicated in **Table 2**.

Table 16. Summary of modelled scenarios, locations and FCLs for Burrard Inlet zones.

Scenario	Burrard Location	Modelled water level + 0.6 m freeboard (m GD)	Wave zone (Y/N)	Wave height addition in wave zone	FCL seaward of wave effect boundary (m GD)	FCL shoreward of wave effect boundary (m GD)*
1	Zone 1	3.6	Y	0.3	3.9	3.6
2	Zone 1	4.2	Y	0.3	4.5	4.2
3	Zone 1	4.6	Y	0.3	4.9	4.6
4	Zone 1	4.8	Y	0.3	5.1	4.8
5	Zone 1	5.8	Y	0.3	6.1	5.8
1	Zone 2	3.6	Y	0.3	3.9	3.6
2	Zone 2	4.2	Y	0.3	4.5	4.2
3	Zone 2	4.6	Y	0.3	4.9	4.6
4	Zone 2	4.8	Y	0.3	5.1	4.8
5	Zone 2	5.6-5.8	Y	0.3	5.9-6.1	5.6-5.8
1	Zone 3	3.6	Y	0.3	3.9	3.6
2	Zone 3	4.2	Y	0.3	4.5	4.2
3	Zone 3	4.6	Y	0.3	4.9	4.6
4	Zone 3	4.8	Y	0.3	5.1	4.8
5	Zone 3	5.8	Y	0.3	6.1	5.8
1	Zone 4	3.6	Y	0.3	3.9	3.6
2	Zone 4	4.2	Y	0.3	4.5	4.2
3	Zone 4	4.6	Y	0.3	4.9	4.6
4	Zone 4	4.8	Y	0.3	5.1	4.8
5	Zone 4	5.8	Y	0.3	6.1	5.8

*Or single FCL used across entire zone if local wave effect study is required in wave zone.

Table 17. Summary of modelled scenarios, locations and FCLs for Fraser River North Arm locations.

Scenario	Fraser River (FR) Location	Modelled water level + 0.6 m freeboard (m GD)	Wave zone (Y/N)	Wave height addition in wave zone	FCL (m GD)
1	FR mouth to Main St.	3.5	N	--	3.5
2	FR mouth to Kincross St.*	4.1	N	--	4.1
3	FR mouth to Main St.	4.5	N	--	4.5
4	FR mouth to Hudson St.**	4.6	N	--	4.6
5	FR mouth to Boundary Rd.	5.6	N	--	5.6
1	Main St. to Boundary Rd.	3.6	N	--	3.6
2	Kincross St. to Boundary Rd	4.2	N	--	4.2
3	Main St. to Boundary Rd.	4.6	N	--	4.6
4	Hudson St. to Boundary Rd.	4.7	N	--	4.7
5	FR mouth to Boundary Rd.	5.6	N	--	5.6

*Kincross St. is east of Kerr St - could use Kerr if major street preferred.
**Hudson St. is between Angus Dr. and Ontario St.

8 FLOOD VULNERABILITIES

8.1 HIGH-LEVEL VULNERABILITY ASSESSMENT

8.1.1 BACKGROUND

Vulnerability refers to the degree to which a system (or element) is susceptible, or unable to cope with the adverse effects of climate change, including variability and extremes. It is a function of exposure, sensitivity (degree to which it may be affected) and adaptive capacity (the ability to adapt) and involves many forms, including at household (or individual), social, institutional, economic, physical, environmental and place levels (Cities and Flooding Guidebook, 2012).

Social vulnerability is the product of social inequalities as well as location inequalities, including community characteristics and the built environment (Cutter, 2003). The elevation above and/or proximity to a hazard – in this case, a coastal flood event – is an important factor in determining the resiliency of a community. Social vulnerability is an important part of the Coastal Flood Risk Assessment (CFRA) but it can be difficult to assess, let alone quantify (Cutter, 2003).

To appropriately assess vulnerability, both geographic and social considerations need to be taken into account to determine what may be harmed by flooding, in other words, the elements at risk (e.g. people, houses, buildings or the environment). Infrastructure and assets can include the building stock, critical infrastructure, transportation routes, and utilities within a community or region. Other miscellaneous items can include the quality and access to parks and recreational space, cultural spaces (outside of the building stock component), and high value habitat (including agricultural potential) (Feb 14th Workshop). In regards to social vulnerability, no fully agreed upon set of indicators exist and these vary considerably from one city to another (Cutter, 2003). Strongly correlated variables include the following (Cutter, 2003; Cities and Flooding Guidebook, 2012):

- Socioeconomic status, gender, age, race and ethnicity
- Value, quality and density of residential properties
- Presence of renters and transient populations
- Commercial and industrial development
- Occupation, education, family structure and expected population growth
- Medical services and health status, social dependence and special needs populations

People and buildings (including their contents) are often of primary concern in a flood event; however, a flood event often acts as a catalyst, or instigates a chain of cascading events, resulting in many secondary or tertiary effects. These effects can occur on an economic, social and community level.

Knowing the approximate extents of the coastal flood hazard in the City supports the importance of integrating flood-receptive designs into land-use and community development planning. Knowing what is in the way is vital, as is appreciating the possible ramifications, to working towards flood risk and flood impact minimization. By conducting a Vulnerability Assessment, the degree of community assets and neighbourhoods vulnerable to coastal flood events can begin to be established. From there, existing assets can be protected, relocated or replaced, as determined by their level of susceptibility to flood levels and importance to vulnerable populations during a flood event.

8.1.2 APPROACH

In order to provide a comprehensive picture of vulnerability in the City, a diverse range of stakeholders were invited to a discussion and feedback session about the present and future coastal flood hazard extents within the City. The overall objective was to have local experts identify and expand on the vulnerabilities in the coastal areas (excluding the Fraser River North Arm). Attendees included representatives from Port Metro Vancouver, Metro Vancouver, BC Hydro, Vancouver School Board, Vancouver Coastal Health, and the City of Vancouver (Sustainability, Engineering, and Emergency Planning departments). Representatives from the Neighbourhood Energy Utility, CN and CPR were not in attendance.

Facilitated by an executive from SFU Carbon Talks at the Creekside Community Centre, the 30 attendees were presented with a brief overview of coastal flood vulnerabilities and cascading effects. They were then guided through a discussion about key concerns due to sea level rise and encouraged to annotate study-area maps and boards with assets, services and populations thought to be in the flood zone and what that impacts of a flood event may be on the City. Workshop documentation is provided in Appendix A of **Annex E**.

Identified assets and areas of potential vulnerability were broken down into four areas of concern: hard infrastructure and utilities; emergency management and preparedness; economic impact; and community and well-being, and further researched. Data collected – including information provided by the City's GIS staff, VanMaps and the Open Data Catalogue – was plotted on a base map of the City. Each element received a geographical marker, most often the registered address or actual building site. Overlaying Scenario 3 flood extents (including freeboard) on this spatial information provided the necessary inputs for a vulnerability hot spot analysis. Elements within the flood zone were marked in red, and elements outside the flood zone were presented in yellow. The more concentrated the elements in a given area, the darker the colour appears there.

For ease of readability, the elements were separated into four hot spot maps with a number of constituent datasets:

- Infrastructure and Utilities – Hydro and pump stations, Neighbourhood Energy Infrastructure around Southeast False Creek, Combined Sewer Overflows, Storm Sewer Overflows and Sanitary Sewer Overflows, and water and GVRD transmission mains.

- Economic – Tourist destinations, major restaurants and hotels, SkyTrain stations, train and bus stations, gas stations, commercial services centres, and water-dependent industry locations.
- Culture and Recreation – Recreation locations, including pools, rinks and sports fields; museums, archives and major galleries and cultural destinations, including heritage sites.
- Community – Social services, homeless shelters, free and low-cost meal locations, senior centres, community centres, non-market housing locations, childcare and pre-school centres, libraries and education facilities.

Datasets related to emergency management and preparedness were treated separately. Further details are included in Appendix B of **Annex E**.

8.1.3 RESULTS

Based on the research, external input and spatial analysis described above, a high level vulnerability report for the Burrard Inlet study area was produced, which included flood vulnerability hot spot maps. The report and the complete set of hot spot maps are available in **Annex E**. **Figure 30** provides a summary hot spot map.

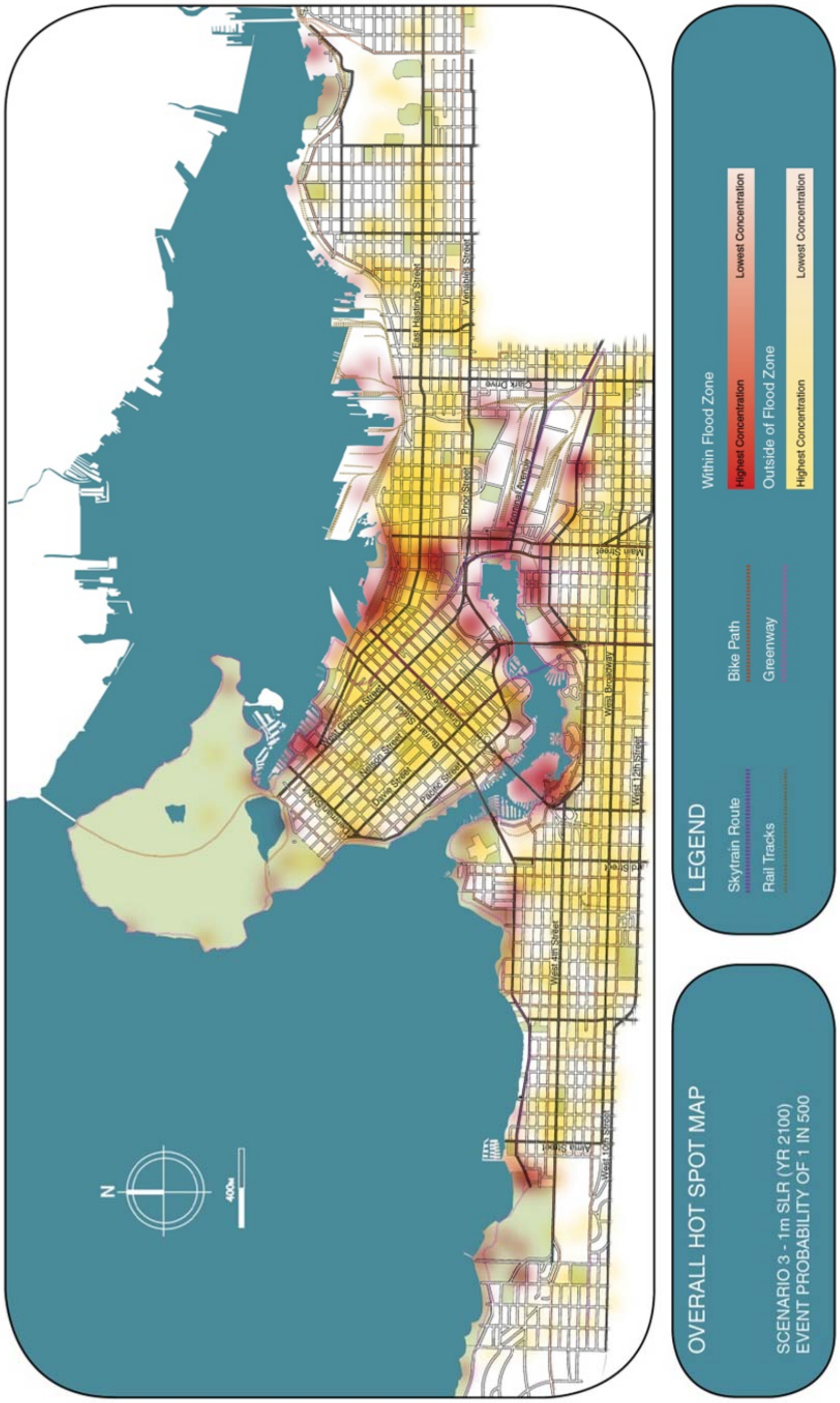

Figure 30. Overall flood vulnerability hot spot map for the City for Scenario 3 based on consideration of several vulnerability elements.

The following observations have been made about flood vulnerability in the City of Vancouver, given a Scenario 3 coastal flood event, assuming present and possible future land-use and present population:

Emergency Management

- Most hospital and care facilities are outside of the flood zone. Those in proximity to the flood zone, and in particular those within the Downtown core, can expect to see increased patient inflows in the event of a coastal flood.
    - St Paul's Hospital is outside of the flood zone but may encounter impacted infrastructure and restricted access. Given its proximity to flooded areas, a spike in patient arrivals should be expected.
    - Vancouver General Hospital is also outside of the flood zone, and may be able to handle the patient overflow from St. Paul's Hospital.
    - Smaller care facilities in proximity to the flood zone may not be able to operate (e.g. Moberly Road on the south side of False Creek west of Cambie Street and near Main and Hastings Street in the Downtown Eastside).
- Most evacuation and access routes are expected to remain relatively clear of inundation during a flood event. Routes particularly at risk of inundation include the north-south corridor along Main Street and Pacific Boulevard. All bridge on-ramps are expected to remain clear of floodwaters.
- In the event of an emergency, the City of Vancouver designates the gymnasiums in their 23 community centers as emergency shelters. Several emergency shelter locations may not be operational in a coastal flood event due to their proximity to floodwaters. In addition, numerous gathering locations are within the flood zone (**Figure 31**). Two are located near Vanier Park, two are near Science World, and five are situated along the water in the West End, Stanley Park, Lost Lagoon, and Coal Harbour. The following gathering places should be moved to locations with a reduced flood risk:
    - Vanier Park sites
    - Science World and Terminal Avenue
    - BC Place Stadium
    - Coal Harbour (may not be fully inundated, but extremely close to floodwaters)
- Three evacuation routes (along W. Georgia Street to either Prior Street or Terminal Avenue; Nelson Street to the Cambie Street Bridge; and Pacific Street to Burrard Street Bridge) will be impeded by the flood zone or directly impacted by coastal floodwaters. The first two evacuation routes will be unusable during a Scenario 3 flood event. Evacuation and access

routes are considered essential transport infrastructure; any reduction in capacity and serviceability will increase the vulnerability of the affected neighbourhoods and populations.

- One police work yard in False Creek Flats is within the flood zone, with three Fire and/or Police stations in close proximity to the flood zone. The stations will likely see an increased demand for their services in the event of a flood. For example, with a portion of Main Street inundated near False Creek, there may be reduced accessibility and increased emergency response time in that area.
- Emergency evacuation and planning for the False Creek and Inner Harbour zones (**Figure 31**) need to be reviewed by City and Emergency Response personnel.

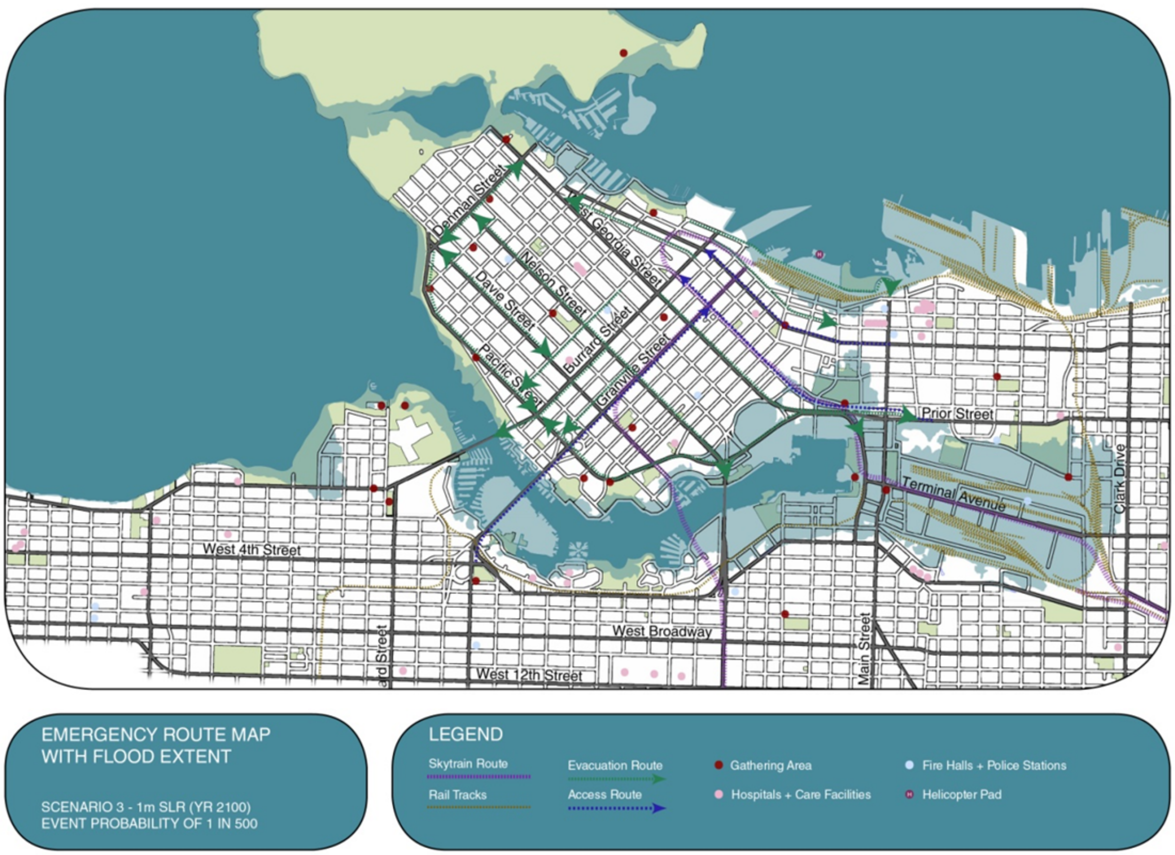

Figure 31. Emergency route map with Scenario 3 flood extents shown.

<u>Infrastructure</u>

- Infrastructure in the flood zone is expected to be relatively resilient in the event of a coastal flood. Risk of damage increases with aging infrastructure.

  - Roads and bridges suffer a complete loss of functionality if inundated. Bridge on-ramps should remain free of floodwaters; however, the collector and adjacent roads under Burrard, Granville and Cambie Street bridges will be inundated.
  - North-south traffic routes will be disrupted: Quebec Street and Main Street will experience some inundation, and Clark Drive will suffer service disruption and increased congestion due to the re-routing of traffic flows. Main Street and Clark Drive play an important role in servicing the Port and are recognized as important truck routes within the City.
  - In terms of east-west connections, parts of Pacific Street and Cornwall Avenue will be inoperable, as well as significant portions of Prior Street and Terminal Avenue. The key east-west connector streets of the Downtown Core (West Georgia St., Nelson St. and Davie St.) are anticipated to remain clear of floodwaters.
  - Strategic utility infrastructure, such as power stations and primary substations, in a flood hazard area is extremely vulnerable to flooding. Without building adaptive capacity and resiliency into the system, the provision of electricity, water and heat may fail. Currently, only the BC Hydro Murrin Substation, located between Main Street and Andy Livingstone Park, is at risk in a coastal flood event.
  - In a coastal flood event, the Neighbourhood Energy Utility (NEU)[10] would shut down (severing all connected residents from heat and hot water) until replacement parts could be ordered and installed. A service disruption of several weeks is possible. The Energy Transfer Stations would be damaged but operable in manual mode by the utility provider. The distribution piping is waterproof, with additional controls in place should water damage occur. Future capacity build-out can incorporate appropriate flood-proofing techniques.
- Uncertainties exist as to how existing combined sewer overflows, storm sewer overflows and sanitary sewer overflows outside of the False Creek Flats area will fare in a flood event.
  - There are a total of 40 stormwater lines and 10 combined sewer overflow lines running across the flood zone with outfalls in Burrard Inlet and False Creek. This infrastructure, whether pumped or gravity fed, may be sensitive to damage and disruption in a coastal flood event, and contamination of flooded areas is possible.
- The primary purpose of the Vancouver Seawall and retaining walls around Stanley Park is erosion protection rather than flood protection. The seawall is presently considered to be in 'average' condition according to the capital improvement plan, with opportunity to upgrade

[10] The NEU uses a heat exchange process to capture waste thermal energy from sewage to provide space heating and hot water to the former Olympic Village site in southeast False Creek.

it in the future. The seawall is directly impacted by incoming waves and incurred damage from storm events in 2012 and 2014.

- With ongoing development throughout False Creek Flats, as well as the continued occupation of buildings along the shoreline, a coastal flood event has the potential to have a major impact on residential and non-residential properties. The foundation, age, structure type and condition of the buildings play an important role in how resilient the City's building stock will be to a coastal flood event.

Transportation

- Bus service is the most resilient aspect of the transportation system as it can be rerouted around inundated areas. Vehicles in the affected areas at the time of inundation may suffer damages. In the wake of a coastal flood event, additional bus capacity may be required to compensate for service reductions and/or obstructions to other modes of transportation.
- Rapid transit service will be impacted (Expo Line, Millennium Line and Canada Line) by a flood. Sections of underground track and service tunnels in the Downtown core, particularly in the vicinity of Waterfront Station, are presumed to flood (February 14th workshop, 2014). While the specific circumstances of flooding are as of yet unknown, there are several possibilities as to how service will be affected.
    - Service west of Commercial-Broadway station (on Expo and Millennium Lines) may cease.
    - Service north of Broadway-City Hall station (on Canada Line) may experience service interruptions.
    - Service connections between the functioning stations (Broadway-City Hall; Commercial-Broadway) and the Downtown core will need to be provided should key electrical and mechanical equipment of the Skytrain system become damaged.
- The Helijet heliport and Seaplane Terminal in Vancouver Harbour may experience service interruptions and operational challenges in addition to damage from debris in a coastal flood event. Access to the North Shore from Downtown Vancouver will be impacted by the operability of the SeaBus terminal, which would be equally affected. Depending on the nature of the event, the terminals may become inoperable.
- Vancouver's commuter rail service, the West Coast Express, may experience service disruption. With enough warning, the trains can be moved out of the flood hazard areas thereby saving them from damage by floodwater or debris, as well as from causing damage to their surroundings. In addition, Port Metro Vancouver's two cruise ship terminals, two container terminals and five bulk terminals on the south shore of Burrard Inlet, as well as the CP rail yard and railway lines will experience operational challenges in moving people and goods.

- Having the transit system in downtown Vancouver partially or completely shut down by a coastal flood event will consequently affect the accessibility, mobility and evacuation of people in flooded areas.

Economy

- Port Metro Vancouver (PMV) lands along the south shore of Burrard Inlet may be inundated. Structural upgrades to terminals and facilities will need to be undertaken in order to minimize operational challenges during a coastal flood event. PMV may be able to offset temporary service disruptions in this area by increased reliance on the Deltaport terminal south of Vancouver. PMV is cognisant that climate change, including sea level rise, may significantly affect port operations and infrastructure.
- Other industrial areas in the City are dependent on transportation infrastructure – in particular, efficient road networks – for moving people and goods. Automotive, apparel manufacturing, food and beverage production, retail, warehouse/distribution and wholesale/commercial services sectors require unimpeded access.
    - The Powell Street Industrial Area is not anticipated to flood during a Scenario 3 coastal flood event.
    - False Creek Flats, including the area along Great Northern Way, is experiencing significant development south of the existing Via Rail/CN rail line. The rail lines (BNSF, CN and Via Rail) just north of the new MEC headquarters may be inundated in a coastal flood event in addition to adjacent light industrial, high-technology, limited residential and related uses along Great Northern Way. All the local roads running south of Great Northern Way are anticipated to remain free of floodwaters and should remain accessible. Vernon Drive is at the eastern extent of the flood zone. Clark Drive is the first accessible north-south arterial road that may remain usable.
    - Concerns include whether or not the existing regulatory framework (Vancouver Building Bylaw and Development Permit requirements) will be sufficient to ensure that industrial and commercial use (particularly for those focused on IT and 'Green'-oriented development) will be able to withstand a major coastal flood event and resulting business disruption.
- Commercial Services, which includes major restaurants, shops, hotels and tourist destinations, within the flood zone will be impacted. Service jobs (particularly local restaurants and retail shops) may be more resilient as they can move between neighbourhoods. Larger projects such as hotels and iconic tourist destinations may be more challenging to relocate (or protect) from both a logistics and cost perspective. Areas at risk include:

  - Cornwall Avenue and Vanier Park tourist attractions (Museum of Vancouver, HR MacMillan Space Centre, Vancouver Archives, Vancouver Maritime Museum and Bard on the Beach)
  - Granville Island (plethora of local artisans and businesses, as well as entertainment venues)
  - Terminal Avenue and Science World area
  - English Bay and local restaurants/shops in the area
  - Waterfront Station (as a transportation hub) and the Gastown district (entertainment, shops and restaurants)

- Vancouver has a significant tourism industry.
  - Most major hotel locations are outside of the flood zone. The Westin Bayshore Hotel may require on-site mitigation measures but the Granville Island Hotel and the Hostelling International-Vancouver Jericho Beach will require significant structural protection/floodproofing or relocation. For the other hotels, most impacts will be secondary or tertiary in nature, including increased demand for accommodation but also disrupted supply chains. The meeting and convention industry may incur a post-flood impact in terms of loss of business and/or disruption to operations.
  - Without appropriate mitigation measures (whether relocation or structural upgrades with flood protection), over the coming decades, the City may see a loss of tourism revenue from these sources. There is, however, time and the capacity to reduce much of the vulnerability.

Culture and Recreation

- Coastal recreation-oriented public spaces will flood and potentially be inundated with debris. Much of the City's coastline is bordered by park or recreational space (the major exception being along the Inner Harbour). In order to maintain access and use of this space, strategies that allow the urban landscape to adapt and regenerate after a flood event will be important.
- Pools, rinks and playing fields are likely to suffer structural and functional damage during and after a coastal flood event, incurring significant reconstruction and rehabilitation costs.
- There will be an economic impact on the businesses and organizations (including the City of Vancouver) that manage the recreation amenities.
- Post-flood effects include damage and obstructions from debris. Objects may become scattered across the water and in near-shore areas. Kitsilano Pool may suffer saltwater

inundation and/or structural damage in a flood, and most sports fields will need landscaping and repair to be serviceable post-flood. Aspects yet to be determined include the financial costs and responsibility for the clean-up.

- The Vancouver Seawall has been an iconic landmark for decades but was not built in anticipation of sea level rise and increasing storm intensities. Looking ahead, the City will need to determine the most reasonable approach for maintaining the seawall given the rising cost implications.
- Many museums, archives, cultural destinations and historic buildings/sites are at risk of flooding. It is extremely difficult to effectively and accurately capture the economic impact of the loss of cultural assets, including their emotional and symbolic value.
    - At greatest risk are the buildings in Gastown and Chinatown, both of which have historical and cultural significance.
    - Structural and functional damage may be expected, as well as a loss of contents and equipment (removable items may be salvageable, but larger items and specialized pieces of equipment may not be).

Community

- At a high level, the City's social services (including homeless shelters, community amenities and education opportunities) are not particularly vulnerable in a flood event. The vast majority of services are provided outside of the flood zone. However, a few localized areas do deliver at-risk services. With proper planning and small-scale relocation, this vulnerability can be reduced or even eliminated. Areas at risk include:
    - Carrall Street Corridor (between Water Street to the north and Keefer Street to the south)
    - Future schools at International Village and Southeast False Creek
    - Existing and proposed childcare facilities at Olympic Village and near Terminal Avenue
    - Existing social housing along Moberly Road (on the south side of False Creek, west of Cambie Street)
    - Granville Island amenities
- In terms of the Downtown Eastside, the area between Carrall Street and Main Street is most at risk. Although this represents a small proportion of the Downtown Eastside (DTES) and limited flood depths, significant secondary impacts may be felt due to the high number of private and non-market Single Room Occupancy (SRO's), non-market housing, and training/livelihood related sites nearby. Impacted sites of significance and the nature of the impact include:

- Crab Park and The Dugout (drop-in centre at 59 Powell Street) – anticipated inundation.
- Insite, Pantages Theatre, Newtown Bakery, Pigeon Park and Portland Housing Society – anticipated service disruption.
- DTES Women's Centre and Carnegie Community Centre – anticipated increase in demand for services.

8.1.4 Discussion

Typically, vulnerability assessments primarily focus on socio-economic considerations, in order to capture the potential for adverse economic, social, and environmental impacts. The results of a coastal flood vulnerability assessment can be applied to urban development planning and initiatives. Urban development plans should not proceed unless the flood risk and expected impacts can be managed to an acceptable level. Effective management techniques can include the use of on-and off-site measures that regulate land use and the conditions of land use through land-use plans, zoning, enforceable policies and regulation that provide necessary instruction for individuals, organizations, businesses and government. This will enable interested parties to determine appropriate types of development, where they can take place and under what conditions, as well as associated costs.

8.2 Stormwater System Vulnerability

8.2.1 Background

The objective of the stormwater and sewer infrastructure assessment is to estimate the extent to which capacity of the existing stormwater system might be impacted by future sea level rise and to estimate what improvements in the system may be needed as mitigation.

The high-level stormwater assessment was limited to the False Creek Flats area drainage system and was performed using a coarse model developed using the United States Environmental Protection Agency (EPA) Storm Water Management Model (SWMM). The model was used to assess infrastructure impacts by simulating flooding depths in the system resulting from a 25-year rainfall event under four of the five sea-level rise scenarios being evaluated in other aspects of this study. The scenarios are described in **Table 1**.

Under Scenario 5, the lowland portions of the study area are all inundated from other flooding sources. It was determined that modelling a submerged stormwater system was not meaningful, so this scenario was not simulated in SWMM.

Reasonable model parameters were used and no calibration or adjustment was made to the model to match observed flooding conditions. The intent of the assessment was to compare the relative impact between the exiting free outfall conditions and the scenarios.

8.2.2 MODEL DEVELOPMENT

Through coordination with City staff, NHC defined an approximately 400-hectare area on False Creek Flats as the model domain and study area. The model was developed using existing data sources by the following methods.

Pipe Network Geometry

The model extents were defined using the City's GIS stormwater inventory, LiDAR elevation data, and consultation with City staff. The model is limited to the largest pipes in the separated stormwater and combined sewer portions of the City's stormwater system. The initial threshold for inclusion of pipes in the model was a 650 mm inner diameter, though some key smaller pipes were added to capture full network connectivity. Invert elevations for most pipes are included in the City's GIS inventory. For consistency with other modelling aspects of the project, and due to a lack of other data, ground surface elevations at the lids of manholes were based on LiDAR elevations.

One unique feature in the system is a large 1800-metre long dual box culvert that flows from east to west under Terminal Avenue. The geometry of that feature was defined using as-built plans provided by City staff. No tide gates are known to provide separation of that box culvert from the False Creek waterway.

Sub-basin Delineation and Land Use

Individual sub-basins were delineated to define the contributing area to each of thirty-nine inlets in the modeled stormwater system. Basin delineation again utilized the City's GIS inventory, LiDAR and feedback from City staff. The sub-basins average 10 hectares each.

The runoff properties of each sub-basin were assigned using an estimate of impervious area and, for pervious surfaces, hydrologic methods developed by the U.S. Natural Resources Conservation Service (NRCS) known widely as curve number hydrology. The areas of connected impervious area and pervious surface area were estimated from a GIS land-use dataset, based on assumed connected impervious percentages shown in **Table 18**. A tree canopy dataset was also used to identify the area of pervious surfaces within the public road right-of-way. All non-impervious surfaces were assumed to be a poor quality grass cover.

Table 18. Land use impervious area classification.

Land Use Class	% Total Impervious Area	% Connected Impervious Area
Commercial	90	85.5
Industrial	90	85.5
Institutional	90	85.5
Open & Undeveloped	0	0
Port Uplands	90	85.5
Recreation and Protected Natural Areas	0	0
Residential - High-rise Apartment	60	48
Residential - Low-rise Apartment	60	48
Residential - Townhouse & Duplex	50	30
Residential - Single Detached & w/Suite	50	30
Residential / Commercial Mixed Use	90	85.5
Transportation and Utility Corridor	90	85.5

Precipitation

The selected design storm applied in scenarios 1 to 4 was a short duration rainfall event with a return period of 25 years. That storm, shown in **Figure 32**, is a nested design storm, developed from 5-, 15-, 30-, and 60-minute rainfall depths with a 25-year return interval distributed in a balanced hyetograph (rainfall distribution). The rainfall depth corresponding to the 1-hour duration was obtained from Metro Vancouver (2009). Shorter durations were not available in the Metro Vancouver (2009) analysis, so they were instead translated from an analysis developed for the City of Seattle (MGS, 2004) by scaling the reported rainfall depths upward by 14% to match the 1-hour rainfall reported by Metro Vancouver (2009). Precipitation was assumed to be unaltered by climate change.

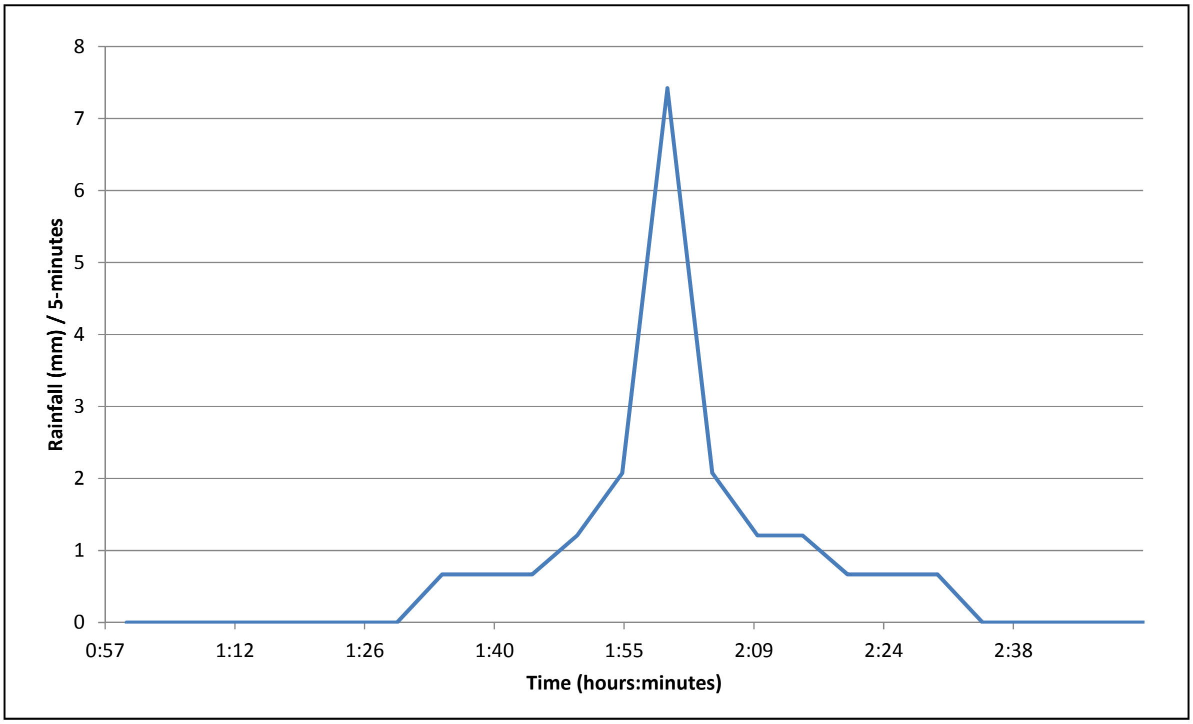

Figure 32. 25-year design storm.

Sea Level

Sea level represents the downstream boundary condition of the stormwater model. Each sea level scenario was defined by assigning a time-series of water surface elevations at the stormwater system outfall to the False Creek waterway (not including freeboard). The False Creek elevations for each scenario were extracted from the overland flow model. The stormwater modelling assumes that peak rainfall and maximum sea level occur coincidentally. Coincident timing represents a conservative, but not unreasonable, assumption.

Existing Capacity

Before running the sea-level rise scenarios, the existing capacity of the system was first evaluated by running the SWMM model with a free outfall condition in which there is no backwater restriction imposed on the outfall of the stormwater system. This model run was used to debug the stormwater network and to determine how much of the flooding simulated in the system is due to existing capacity limitations in the pipe network independent of imposed sea level boundary conditions. The results of the free-outfall simulation are presented as **Figure 33**. Flooding depths at each of the nodes are coloured as indicated in the legend.

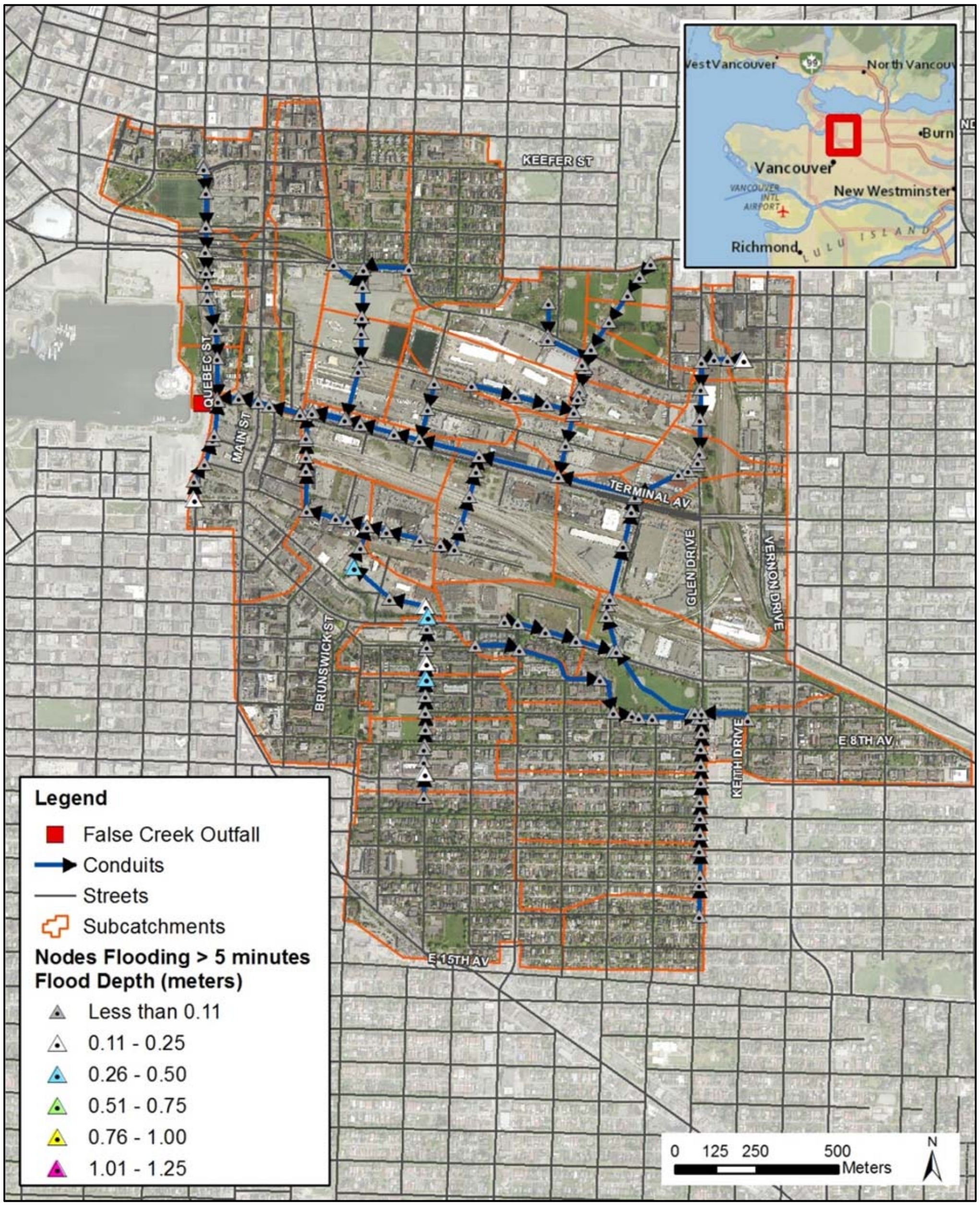

Figure 33. Simulated flooding depths for a free outfall condition with a 25-year design storm.

8.2.3 RESULTS

Each of the four sea-level rise scenarios was simulated using the SWMM model to calculate the flooding depth at any manhole or inlet node in the system. A node is considered to be flooding if the simulated water level exceeds the rim elevation, indicating overtopping onto the street. The locations and simulated flooding depths for all flooding nodes in each sea level scenario are identified in **Figure 34** through **Figure 37**. To facilitate comparison between scenarios, **Table 19** presents flooding depths for four selected nodes that show flooding in at least one of the four scenarios. The locations of the comparison nodes are identified in **Figure 34** through **Figure 37**.

Table 19. Flooding nodes for tidal scenarios.

Name	Scenario	Flooding Depth (m) – by Node ID			
		129919	400531	414693	133262
1	Existing Conditions	0.3	0.1	0	0
2	0.6 m rise, 1:500 Hazard	0.5	0.5	0	0
3	1 m rise, 1:500 Hazard	0.8	0.9	0.2	0
4	0.6 m rise, 1:10,000 Hazard	0.9	1.0	0.3	0.1

The extents of simulated flooding in Scenario 1 (**Figure 34**) are substantially more than that simulated in the free outfall test scenario shown in **Figure 33**, indicating that even at current sea levels, system capacity in some areas is limited by outlet conditions. Most of the simulated flooding in this scenario is limited to the south side of Terminal Avenue. No calibration or adjustment was made to the model to match observed flooding conditions but given the assumption of coincident sea-level rise and frequency of rainfall, the simulated flooding extents are not surprising.

In Scenarios 2, 3 and 4, the flooding extents and depths increase substantially, covering most nodes in the lowlands. The simulated flooding depths at sample nodes 129919 and 40531 increase to half a metre in Scenario 2 and then approach a full metre of depth in Scenarios 3 and 4. Smaller flooding depths are tabulated for nodes 414693 and 133262.

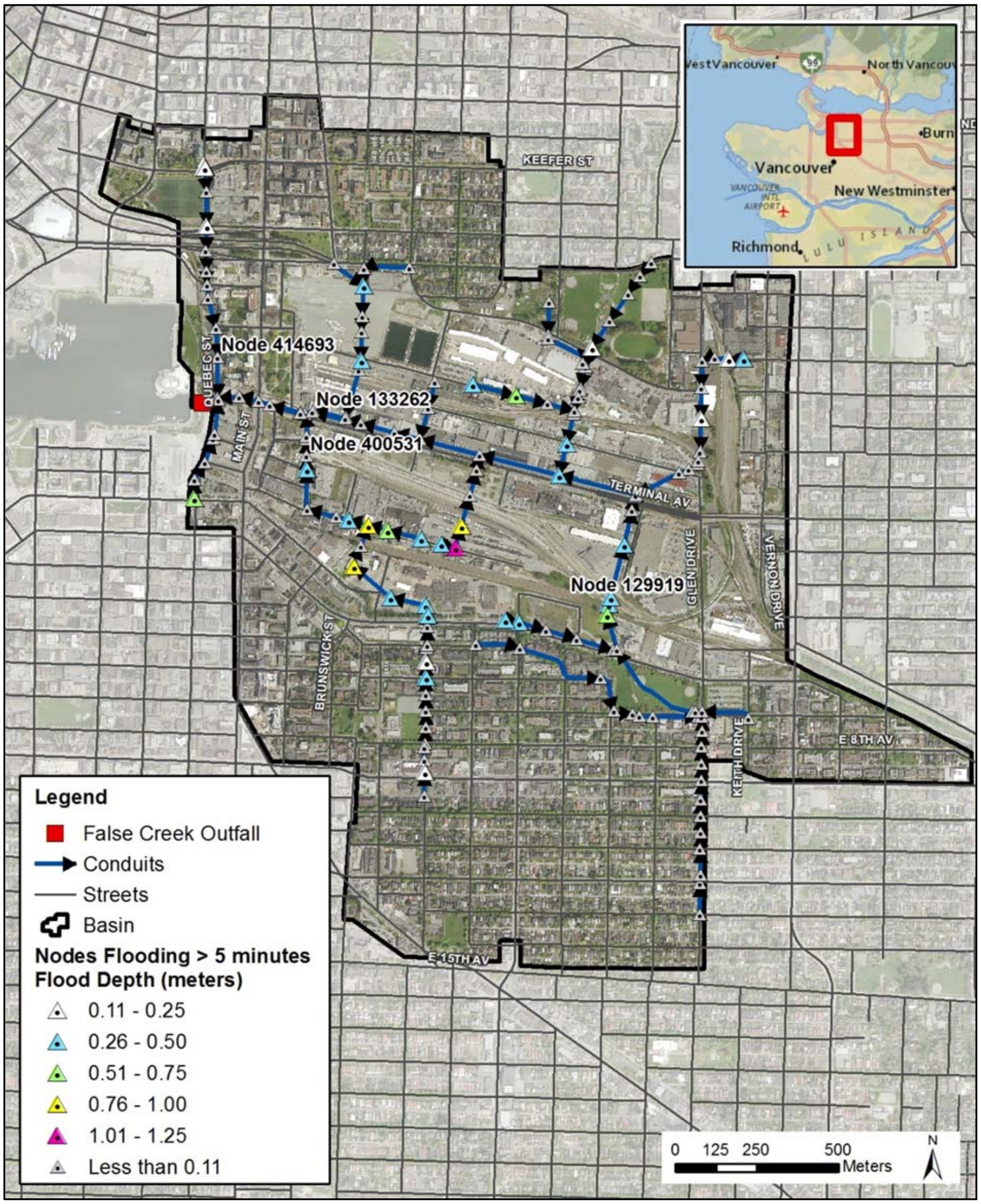

Figure 34. Simulated flooding depths for Scenario 1 with a 25-year design storm.

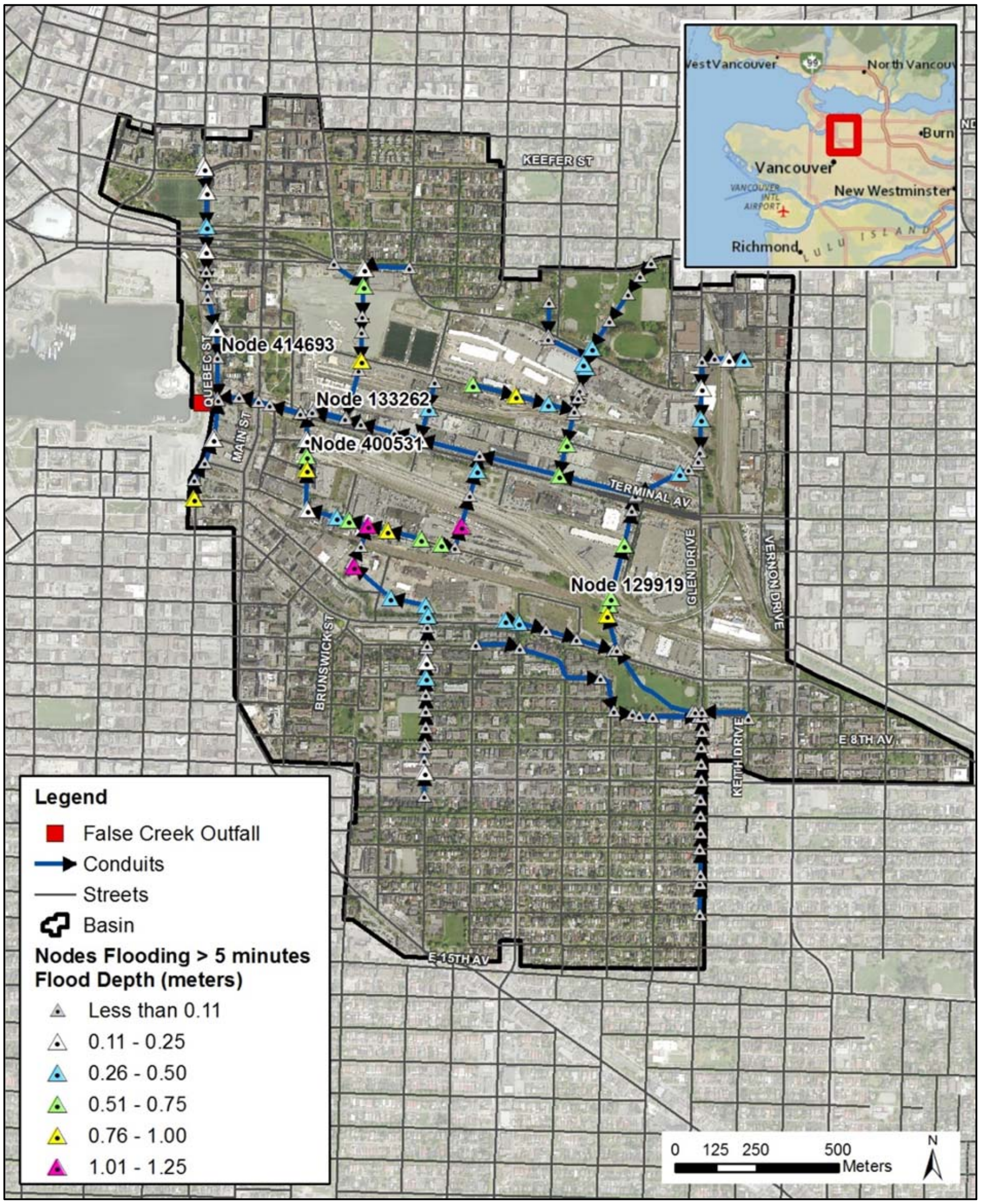

Figure 35. Simulated flooding depths for Scenario 2 with a 25-year design storm.

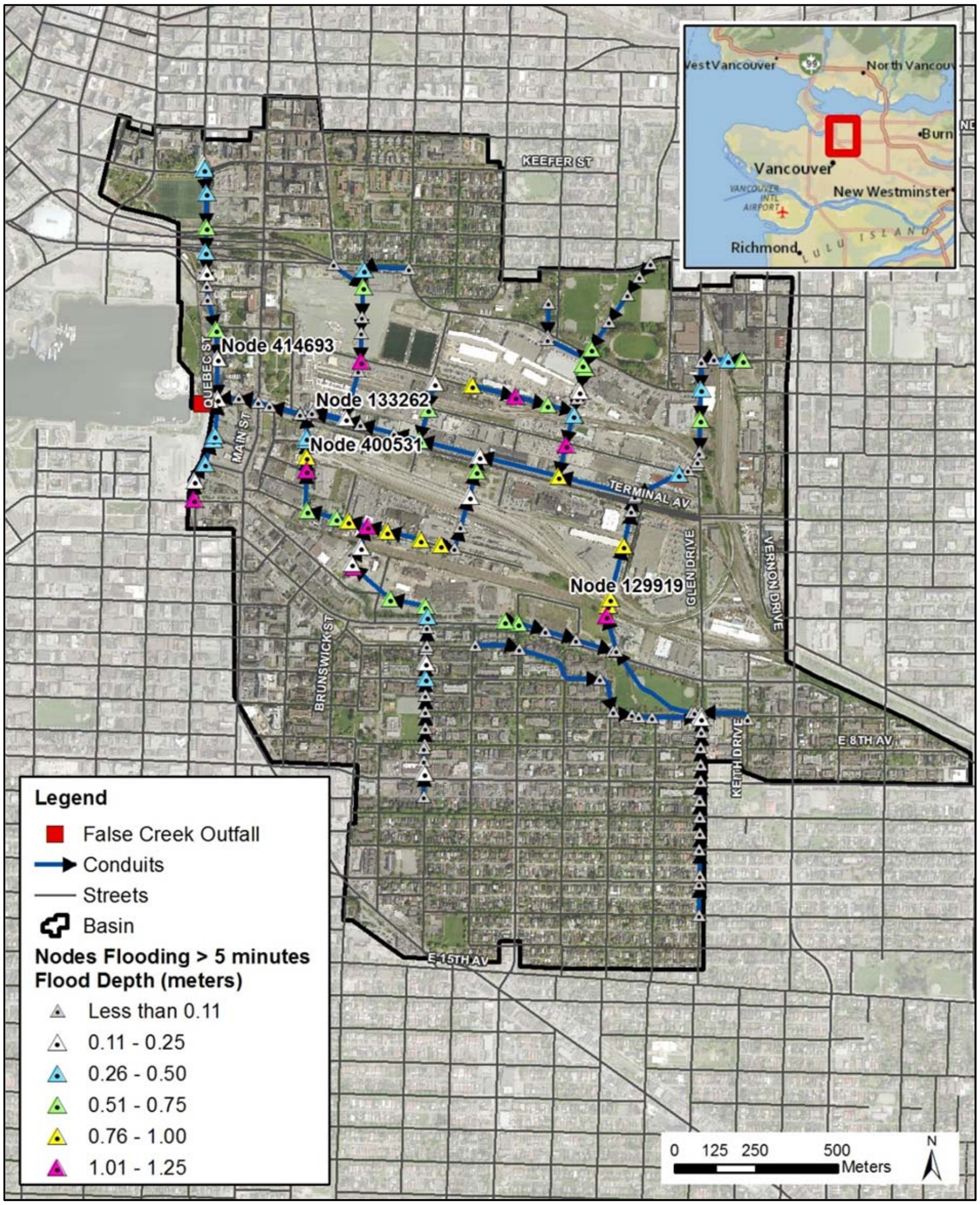

Figure 36. Simulated flooding depths for Scenario 3 with a 25-year design storm.

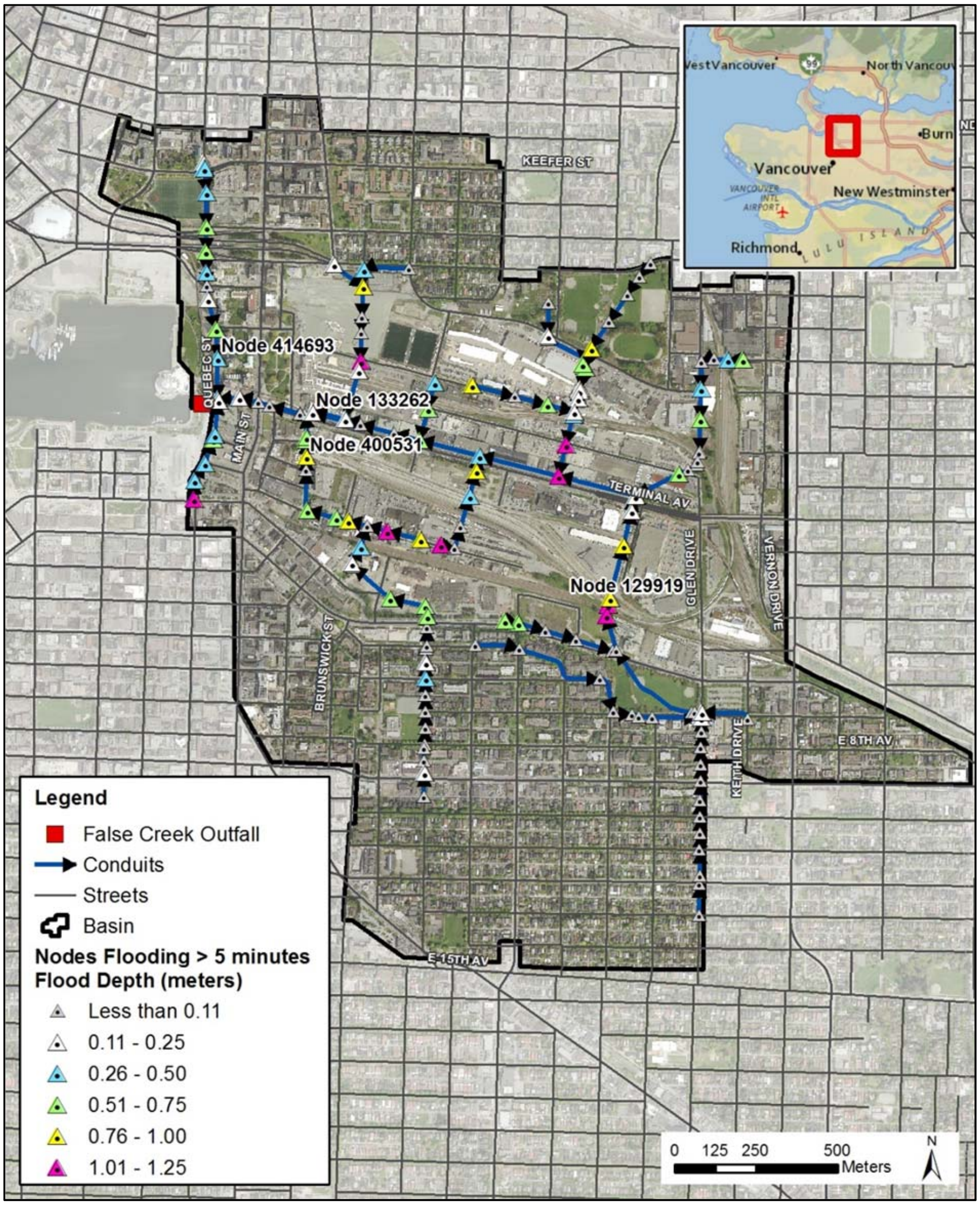

Figure 37. Simulated flooding depths for Scenario 4 with a 25-year design storm.

8.2.4 REQUIRED PUMPING CAPACITY TO PREVENT STREET FLOODING

Flooding that is predicted as a result of discharge restrictions due to sea-level rise could be addressed by adding capacity to pump stormwater over a floodwall and into the inlet. A planning level estimate was performed to identify the pumping capacity needed to prevent flooding in the False Creek study basin for the 25-year design storm. Pump sizing was based on the following four interrelated components:

- A hydrograph of inflows to the pump station,
- Gravity discharge rate from the system into the inlet,
- Storage capacity in a pump station wet well or forebay and elsewhere in the stormwater system, and
- Discharge rate of the pumping system

For the study basin, it was assumed that a new pump station would be sited at the outfall near the intersection of Quebec Street and Terminal Avenue and that, aside from the stormwater pipe network, the only stormwater storage provided in the basin would be incorporated into the new pump station in the form of a wet well or forebay. This assumes that no new engineered storage facilities will be constructed in the basin and that stormwater will not be stored in the streets in the form of street flooding. A hydrograph of inflows to the hypothetical pump station forebay was calculated by first upsizing all of the undersized pipes in the stormwater model and then using the model to calculate the runoff entering the pump station.

If the system is able to discharge via gravity outflow during storms, then the needed pumping capacity would be smaller than a system that relies only on pumping. The feasibility of gravity outflows was evaluated for this system, but the peak tidal stages are at elevations of 3 m or higher in all scenarios, which is too high to allow gravity discharges without concurrent street flooding due to backwater levels. This is even the case in the existing condition scenario, largely because of the assumption of coincident high tide and peak rainfall.

In the absence of gravity outflow, runoff has to either be stored or pumped out of the system. The needed pumping rate is thus a function of both the inflow and the provided storage volume. For example, it is possible to store a complete runoff hydrograph without allowing any discharge if an adequately large storage volume is provided. Similarly, water levels can also be controlled by using very large pumps with a negligible storage volume. The relationship between storage volume and pumping capacity for this system is shown in **Figure 38**. A pump station sized with any of the specifications represented by the red curve would control flooding in the 25-year storm in the study basin.

The ideal pump station would be selected by balancing the cost of storage volume and pumping capacity. Such an assessment is outside the scope of this effort, so a pump station volume was assumed instead. **Figure 39** shows an example of the relationship between runoff inflow rate at the False Creek outfall, a pump station forebay storage volume of 12,500 cubic metres, and maximum pumping capacity of 10 m^3/s. This volume was selected because it could be achieved by converting one parking lot at the intersection of Quebec Street and Terminal Avenue to a forebay with a facility depth ranging from 1 to 2 metres. This facility was then added to the stormwater model and the model was run with sea-level rise Scenarios 1 through 4 to confirm that no interior flooding would occur during the 25-year storm. It should be noted that this does not account for surface flooding from sea level overtopping the existing floodwall. However, even in Scenario 5, if a floodwall capable of keeping seawater at bay is constructed, then this pump station would have adequate capacity to control water-levels within the stormwater system in the 25-year storm.

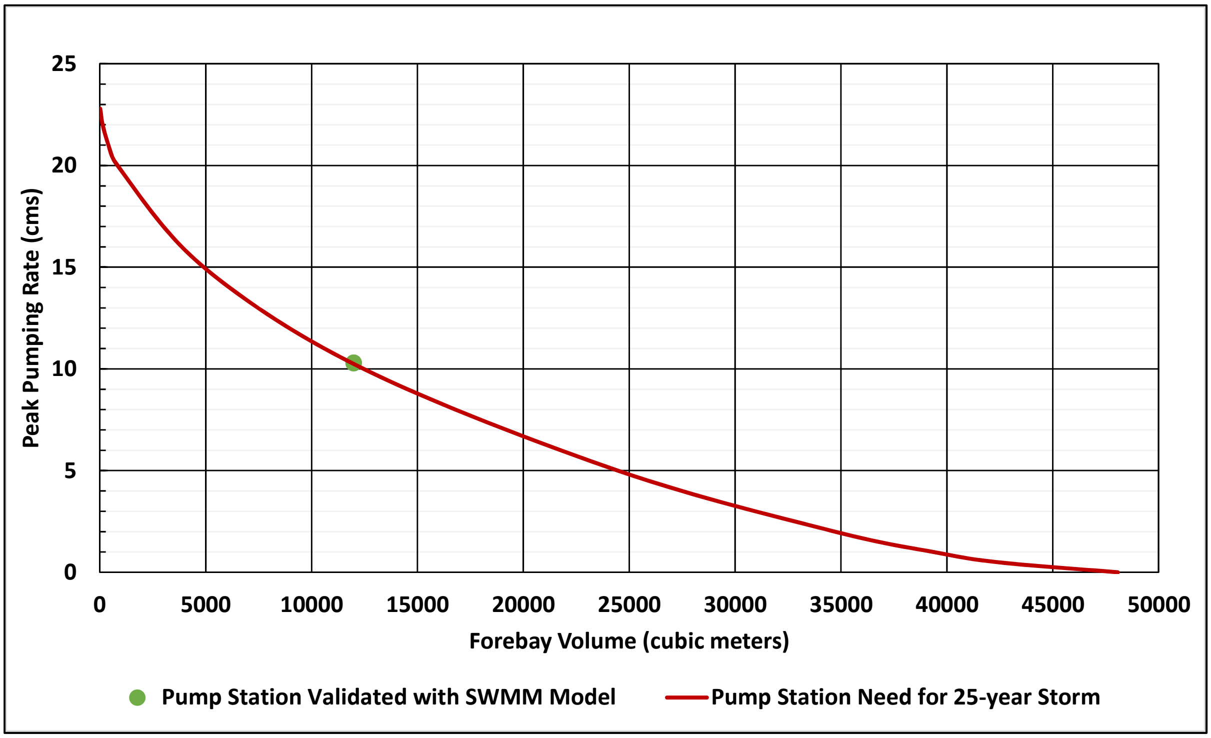

Figure 38. **Required forebay volumes and peak pumping rates for 25-year storm in the False Creek basin.**

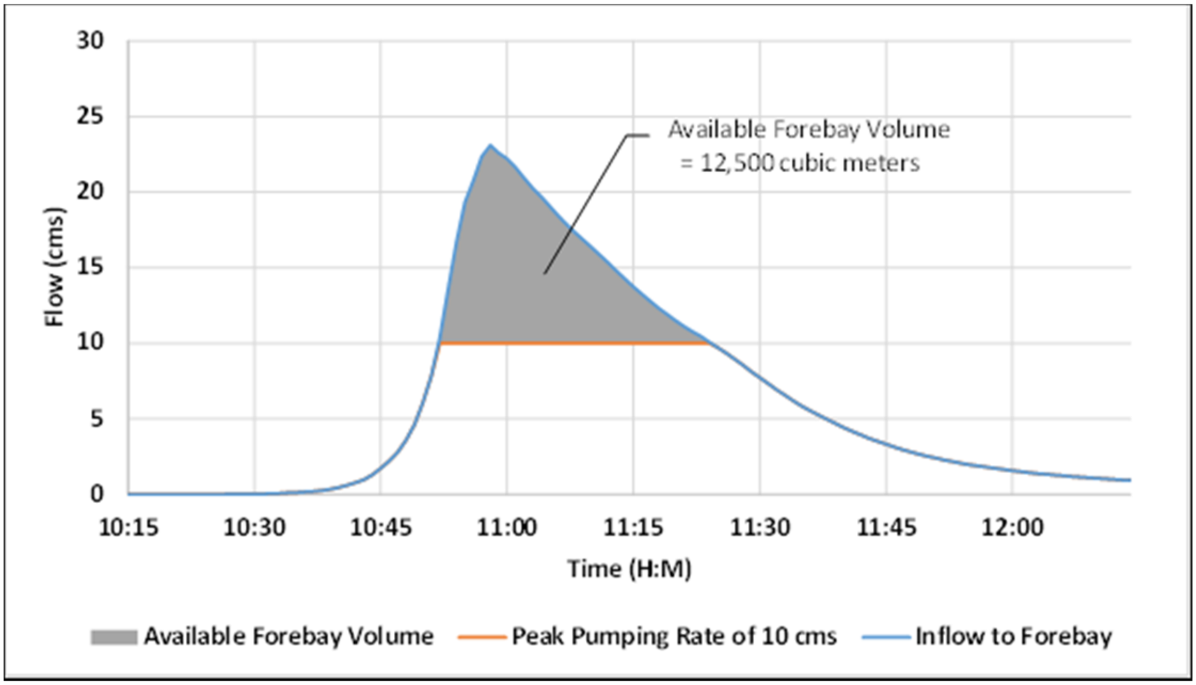

Figure 39. Hydrograph showing inflows to a pump station located at Quebec St. and Terminal Ave., forebay volume needed with a peak pumping rate of 10 m^3/s is shaded grey.

8.2.5 Discussion

The evaluated scenarios indicate that a substantial decrease in the capacity of the stormwater system in the lowlands of False Creek can be expected with sea-level rise, and without mitigation, flooding extents and depths will increase substantially. The most effective solution to mitigating sea level backwater impacts is likely to be the addition of pumping capacity to convey flows over a floodwall at the system outlets. The pump station needed to provide that pumping capacity would be large, needing a maximum pumping rate on the order of 10 m^3/s if a forebay volume of 12,500 cubic metres were provided.

The flooding extents and required pumping capacities calculated as part of this effort are expected to be somewhat conservative. This is particularly due to the assumption that peak rainfall and maximum sea level occur coincidentally. No calibration of runoff from the basin was included in this analysis but all factors were assigned using commonly accepted parameters for runoff and hydraulic response.

8.3 Flood Vulnerability along the Fraser River

Flood risks along the North Arm of the Fraser River include storm surges, extreme winter tides and freshet flooding. Off-site flood protection along this reach consists of a mix of structural approaches, predominately rock revetments but also dikes, metal and wood timbered sheet pile walls, lock block retaining walls and sandbags—nearly all of which has been built by private property owners and would likely not meet current provincial diking standards. On-site flood protection consists of elevation rise through fill placement and non-habitable uses below flood construction levels. Recent developments include higher intensity industrial developments, such as business parks, and higher density residential communities. As a result, the population and building values within the floodplain are increasing.

The floodplain along the Fraser River contains a wide range of land uses and densities. It includes single-family residential lands in the Musqueam IR, both for on-reserve housing and residential leasehold purposes; the rural and equestrian Southlands area, most of which is in the Agricultural Land Reserve; townhouses and apartments in Fraser Lands; and major industrial areas from east of the Knight Street Bridge to west of the Arthur Laing Bridge with uses ranging from outdoor storage of aggregate supplies to office and business parks. Major new development includes multi-family development in East Fraserlands and around the Marine Drive Canada Line station as well as intensive employment designation in the Marpole Plan south of the Marine Drive Canada Line station.

While a comprehensive vulnerability analysis of the Fraser River reach has not been done, a number of key infrastructure elements and facilities have been identified as being potentially vulnerable to flooding with future sea level rise. These include, but are not necessarily limited to, the following:

- City of Vancouver Operations Yard (Manitoba Street north of Kent Ave.)
- Coast Mountain Bus Company's Vancouver Transit Centre, 9149 Hudson Street
- BC Hydro Kidd #1 substation, constructed in the 1950s (south of Kent Ave. and immediately east of Cambie)
- GVS&DD regional trunk sewer lines
- Musqueam Cultural Education Resource Centre
- Musqueam administration buildings

In addition, there are several Provincially-designated heritage sites along the Fraser River, near Musqueam IR, that could be vulnerable to negative impacts from sea level rise and erosion. There are also several foreshore parks along the river that could be negatively impacted, in particular Fraser River Park, which has limited erosion protection.

9 FLOOD CONSEQUENCES

9.1 BACKGROUND

A flood risk assessment allows decision makers to move beyond knowledge of hazard zones and vulnerabilities, and towards an understanding of the consequences of flooding to their community. It requires information from a flood hazard assessment, such as the expected depth of flow, as well as information about the assets and people that are vulnerable to flooding. By combining these two data sets, potential losses due to flooding can be identified. Flood consequences for various hazard scenarios were calculated for all the floodplain areas in the City, including along the Fraser River shore. The project approach to flood impacts, consequences, losses and risk are discussed in detail in **Annex F** and summarised here.

9.2 HAZUS MODELLING

Hazus, a model initiated by the U.S. Federal Emergency Management Agency (FEMA) in 1992, and recently adopted by Natural Resources Canada, is a standardized methodology for the calculation of potential losses from natural hazards. The City elected to use this tool for their flood consequence assessment. Further details on the software and associated methodology are provided in **Annex F**.

Hazus, like most risk assessment tools, calculates only direct tangible and some indirect tangible damages and losses[11], providing a significant amount of information about damages and losses to buildings in particular (**Figure 40**). It also provides limited loss information pertaining to people as well as indirect economic losses. Damage and loss results are calculated based on an asset inventory (elements of value on the floodplain) and the hazard itself (the location and depth of the water). This information is then combined with depth-damage curves from Hazus, which are curves that describe the damage to a building based on water depth as a percentage damage. Damage results are subsequently translated into dollar and social losses based on standard algorithms. Detailed information on the development of the asset inventory and the use of depth-damage and loss curves is presented in **Annex F**.

[11] Direct impacts describe all harm that relate to the immediate physical contact of water to people, infrastructure and the environment. 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. 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. More detail is on the definition of these terms is provided in Annex F.

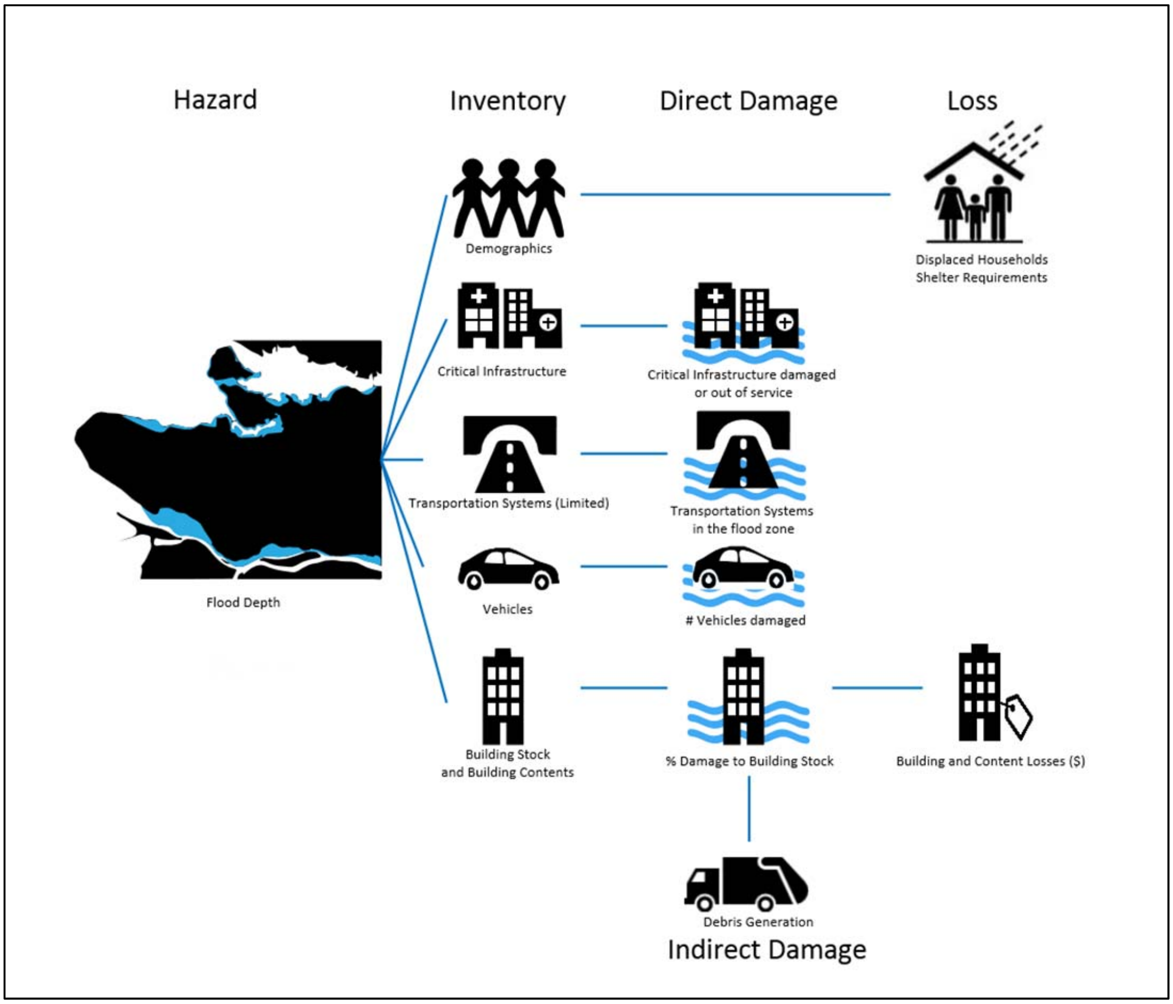

Figure 40. Hazus modelling structure for City of Vancouver.

This project is the first major use of the Canadian version of the Hazus flood module, and in fact, was limited to the use of the beta version of the program; the initial release was anticipated for late summer 2014. Throughout the course of the consequence assessment, many limitations and gaps were identified in the use of this program in a Canadian-urban context such as the City of Vancouver, including the uncertainties associated with the use of the default depth-damage curves in Hazus. The limitations along with recommendations on next steps are presented in **Annex F**.

It should be noted, however, that Hazus is a well-regarded tool for flood risk assessment, and that there are few alternatives to this software. Hazus has also been adopted by the Federal government that has invested resources into populating the inventory database, especially demographic information. This was a valuable element in the Hazus modelling for the City.

9.3 Consequence Results

City staff ran the Hazus model for each of the hazard scenarios described in **Table 1**. The results were then provided to the consultant team for analysis. The following summarises the results of the Hazus runs; more detail is provided in **Annex F**. As this is the first major use of Hazus in Canada, careful consideration was given to the format of the results to ensure that the information is useable and that results with large associated uncertainties are not presented as rigid numbers. Due to many uncertainties associated with understanding the built-form of the City into the distant future, no results are presented here for Scenario 5 – Year 2200, 2 m of sea level rise. The presented results and formats have been developed based on conversations with the City, other users of Hazus (FEMA Region X and Region IV) and Natural Resources Canada.

9.3.1 People

Hazus reports both the number of displaced households and the expected number of people who will seek shelter at public shelters. The number of displaced households is calculated as a function of the number of housing units in or near to the inundated area. Shelter needs are calculated as a function of the number of the displaced households, the number of people within the household and their perceived need for public shelters; wealthier families are assumed to be less likely to seek shelter in a public shelter for example.

Table 20 shows the results of the demographic calculations within Hazus. A spatial representation of the number of people who will seek shelter is shown in **Figure 41**.

Table 20. Hazus results on people and housing affected under scenarios 1 through 4.

Scenario	Number of Displaced Households	Number of People Who Will Seek Shelter
1	1,700	5,000
2	2,700	8,000
3	4,000	11,900
4	4,800	14,300

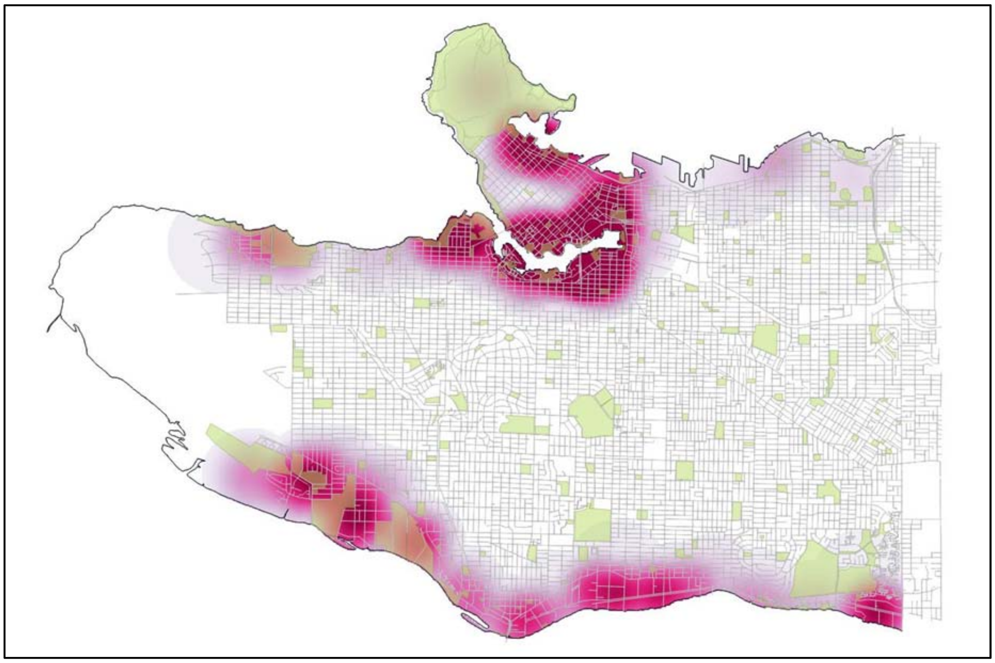

Figure 41. Hot spot map of shelter needs for 1 m SLR, 500-year storm (Scenario 3).

The Hazus results show that significant impacts will be felt directly by the residents of Vancouver if a flood event were to occur, even in the present-day, when 1,700 homes would likely require evacuation for a short period of time. Many of these homes are in the False Creek area, where there is a relatively dense residential community, and a significant number of non-market housing units.

9.3.2 ESSENTIAL FACILITIES

Hazus reports on damage to essential facilities, which are defined as fire stations, hospitals, police stations and schools, and is simply based on the location of these facilities within the floodplain.

The Hazus results for the City indicate that there are no essential facilities within the flood extents of scenarios 1 through 4. The largest scenario (Scenario 5), which consists of 2 m of sea level rise and a significant, 10,000-year storm, results in moderate damage to one school and loss-of-use of another school in the Kitsilano neighbourhood. The lack of essential facilities reported by Hazus is largely a function of the limitations of the software – it only considers fire stations, hospitals, police stations and schools. There are many other critical infrastructure elements that would be at risk in a major flood: pump stations, power substations, public works yards, etc. These are documented in **Section 8**.

9.3.3 BUILDING STOCK AND CONTENTS

Hazus provides significant outputs that relate to building structures. For this assessment, the City employed a user-defined (UDF) approach to the building asset inventory. This effectively means that, as much as possible, the attributes of each individual building in the floodplain was incorporated into the model. This approach is preferred to the default census block approach as it provides building-specific outputs. The program reports significant detail on expected damages to building structures along with the anticipated cost in dollars associated with this damage. Further information on the costs associated with damage to building contents is also provided. All this information is given on an individual building scale, and therefore, inferences can be made based on location, zoning, construction type, etc. Select results are presented here, and more details can be found in **Annex F**.

BUILDING DAMAGES

The total number of damaged buildings is shown in **Table 21**, with the breakdown by level of damage in **Figure 42** and the breakdown by occupancy type in **Figure 43**.

Table 21. Hazus results on building stock affected under scenarios 1 through 4.

Scenario	Number of Damaged Buildings
1	484
2	666
3	817
4	862

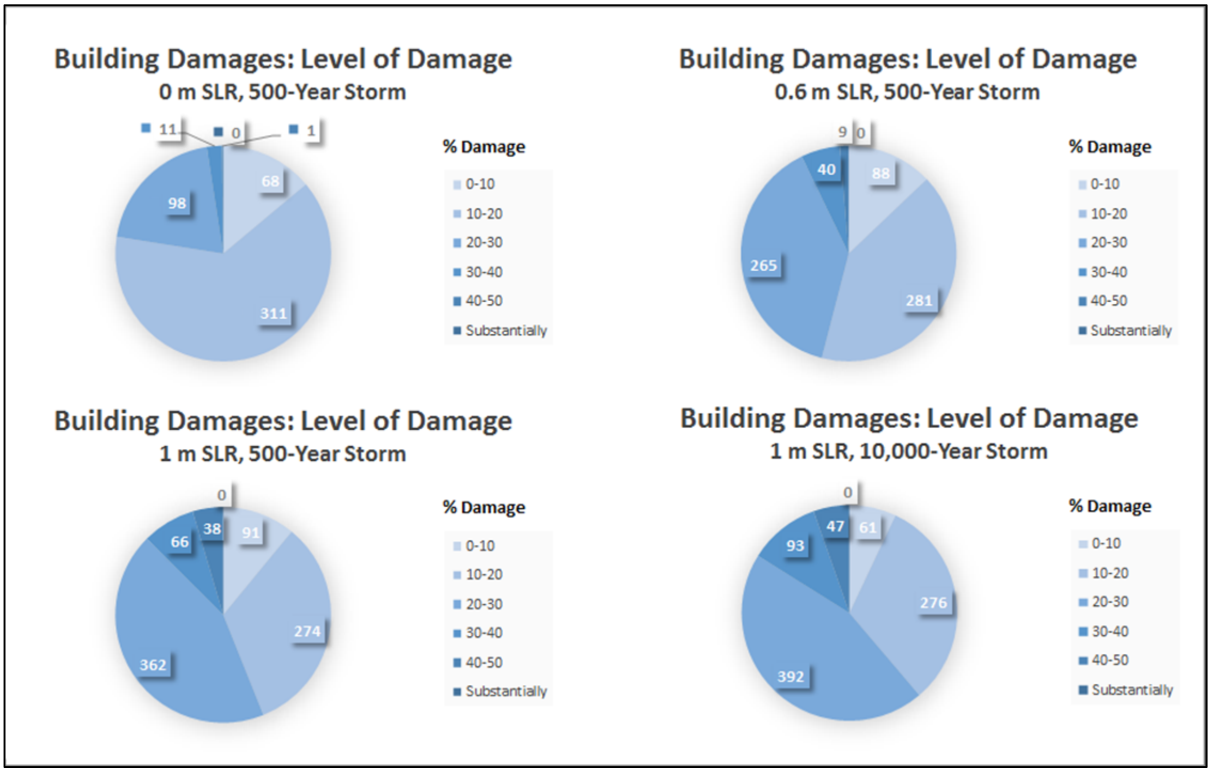

Figure 42. Building damages categorized by level of damage under scenarios 1 through 4.

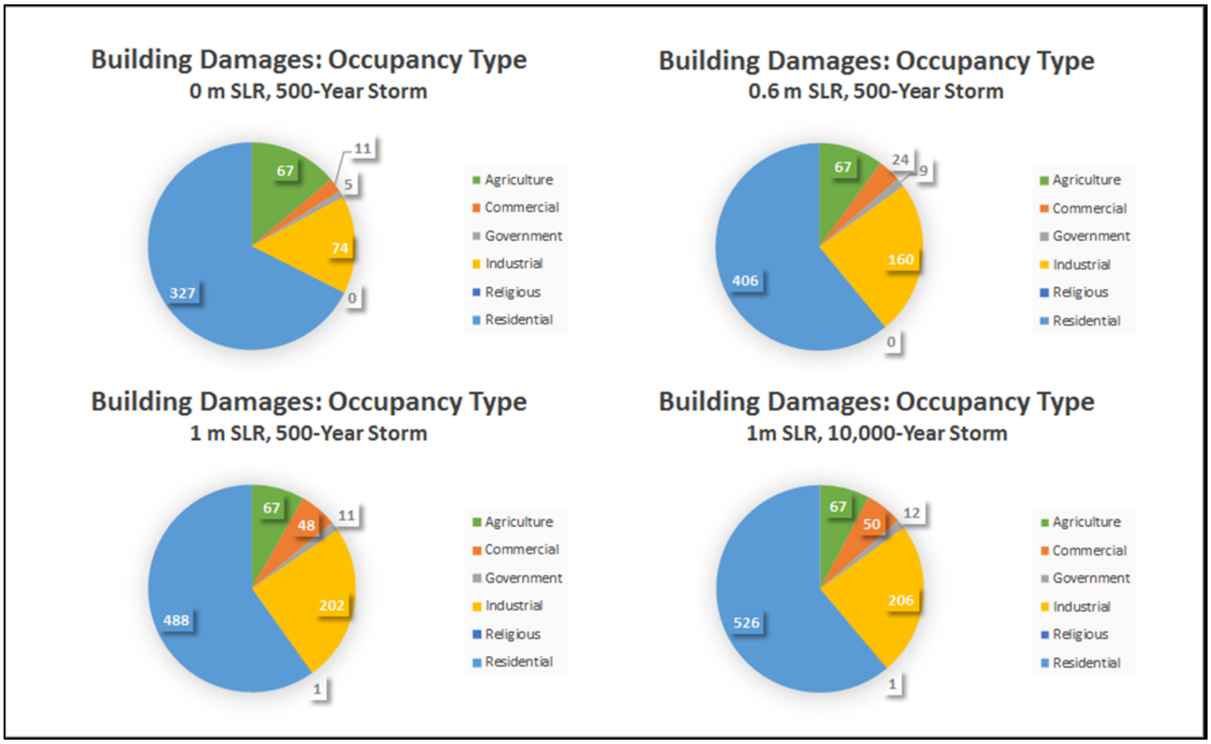

Figure 43. Building damages categorized by occupancy type under scenarios 1 through 4.

There are significant anticipated building damages as a result of coastal flooding in the City, with almost 500 damaged buildings assuming a 500-year storm with present-day sea level conditions. The number of damaged buildings increases with the severity of the storm and flood event, with 860 damaged buildings under Scenario 4. Another important consideration is the level of damage that is incurred under the various scenarios. For Scenario 1, in the present-day, more than three-quarters of buildings suffer minimal damages (< 20% damage), which correlates to a building "getting its feet wet" and requiring the replacement of floors, carpets, lower drywall, etc. but no major renovations. However, under the same storm scenario with 1 m of sea level rise (Scenario 3), there are significantly more damaged buildings, and each of these buildings suffers greater damage. Thirty-eight (38) buildings in this scenario are shown to have damage approaching the 50% mark, which is generally considered to be the "write-off" point.

When looking at building damage by sector, it is clear that the majority of buildings at risk are residential homes; this is true through all scenarios. Significant industrial building damage is also expected through all scenarios; the industrial buildings are primarily located in the Fraser River floodplain, with some additional buildings, especially for the larger flood events, along the Burrard Inlet foreshore. In additional to direct building damages, industrial buildings would incur significant losses to contents and inventory (which in some cases could exceed the cost of building damage).

BUILDING LOSSES

Hazus also provides estimates of costs (in dollars) and losses for building stock damage. However, the depth-damage curves used to calculate these costs are based on U.S. data. As such, the resulting damage estimates are considered unreliable for Vancouver and have not been presented at this time. Section D of **Annex F** provides a more detailed discussion on the shortcomings of the depth-damage curves and recommended next steps for refining this aspect of the Hazus model for use in Canada.

9.3.4 DEBRIS GENERATION

Hazus estimates the amount of debris that will be generated by a flood. Debris generation can be a significant impact of a flood; this was evident in the 2013 Calgary flood event when debris piled up outside buildings in the immediate aftermath of the flood. The model calculates debris quantities based on damages to buildings and on construction type and includes finishes (drywall, insulation, etc.), structural components (wood, brick, etc.) and foundation materials (concrete, rebar, etc.). Debris is reported in tons and as the number of truckloads required to remove the materials. Truckloads of generated debris for the various scenarios is presented in **Figure 44**. The modelling shows that there will be significant debris generated as a result of a flood event, even in the present-day. This would pose a significant waste management problem for the City and Metro Vancouver.

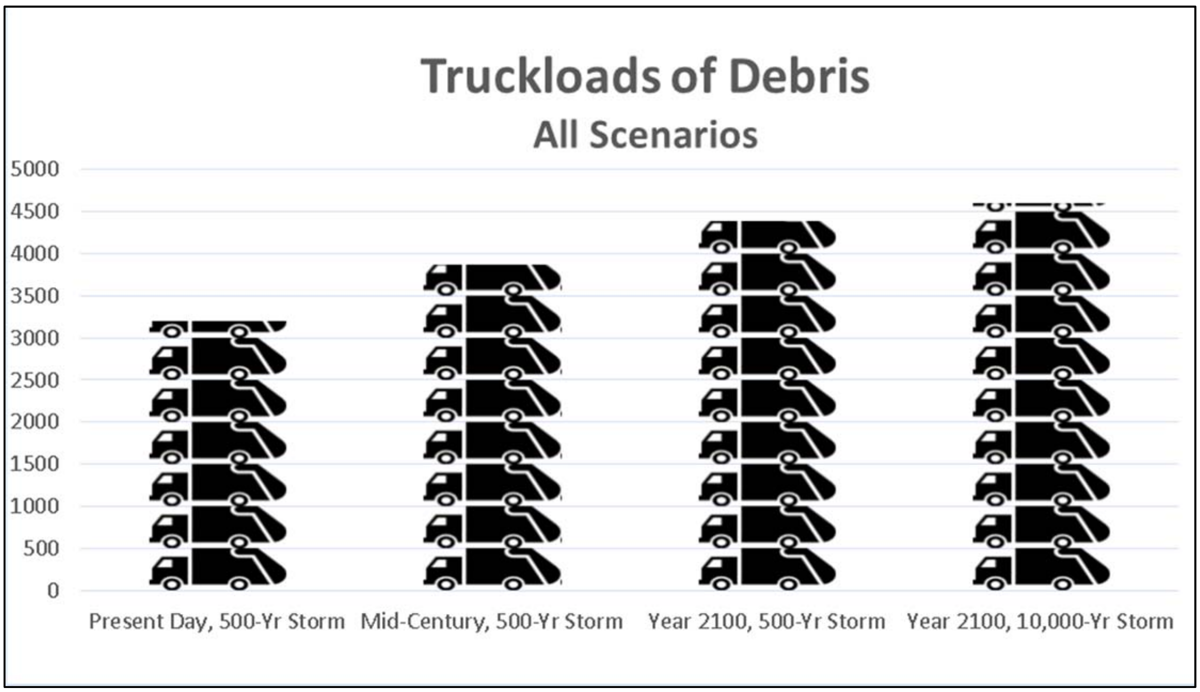

Figure 44. Truckloads of debris generated under Scenarios 1 to 4.

9.4 SUMMARY

The Hazus modelling, although limited in scope relative to the larger scale of impacts expected from a flood event, does provide some excellent insight into expected damages and losses that might be experienced by the City. In particular, it shows that a coastal flood event will have a big impact on people, first and foremost, displacing thousands of families in the short term, and causing disruption to hundreds of families while their residences are cleaned and repaired post-disaster. The results also show that a number of industrial buildings would be impacted, particularly along the Fraser River. These buildings would also incur significant losses of contents and inventory as a result of flooding.

Due to challenges with applying the U.S.-based software to Vancouver, damage costs were considered unreliable and have not been presented in this report. It should also be noted that, while direct tangible costs would likely be significant, they only describe a small portion of the likely impacts from a coastal flood event. Indirect and long-term costs would be many times greater, and the many intangible impacts can have a significant toll on individuals, communities, the region and the country-at-large. Further qualitative details on some of the intangible and indirect impacts are provided in **Annex F**.

For context on the potential damages of a major flood, a review was done of the costs incurred in southern Alberta as a result of the 2013 flood. The total cost of that event is now estimated to be $7B. An estimated 4,000 businesses and 2,000 homes were directly impacted, and more than $50 million was spent on emergency response. While the flood in southern Alberta is not directly transferable to Vancouver as it was caused by river flooding rather than a coastal event, the costs do illustrate the widespread impacts of a major flood event. Similarly, a 2013 flood event in Toronto caused nearly $1B in damages and disrupted transportation into and out of the city. Hurricane Sandy – the most significant coastal flood event in North America to date – caused an estimated $20B in damages in New York City. Based on these recent examples, the consequences of a major coastal flood in Vancouver could be costly and far-reaching, particularly given its central economic role in the region.

9.5 RECOMMENDATIONS

There are many uncertainties associated with the use of the default depth-damage curves in Hazus. However, this is the best available information at this time. In order to move this project forward, the following recommendations are made:

1. Hazus Canada is the best available tool for flood consequence assessment in Canada today. It does, however, have many fallibilities, most of which have been identified in this report (see **Annex F**). At this time, we recommend that the results from the Hazus modelling be used as a basis for going forward with flood mitigation planning in Phase 2. However, the

results should be viewed at an aggregate, big-picture scale, for relative comparisons of damage; they should not be used for detailed cost-benefit assessments at this time.

2. Natural Resources Canada is now aware of the issues with the default stage-discharge currently used in the Canadian version of the program. We recommend that the City work with Natural Resources Canada and other stakeholders to complete a comprehensive review of the curves in the program, and to update the information with more appropriate curves from non-U.S. flood damage databases.

3. Canada has recently experienced several damaging floods: Calgary and Toronto in 2013 and Richelieu in 2011, for example. It may be possible to pursue the development of Canadian-specific curves from these events with appropriate research partners. Potential partners include Natural Resources Canada, Alberta Environment and Sustainable Resource Development, Public Safety Canada, the Institute for Catastrophic Loss Reduction at Western University and the insurance industry.

4. The City should create a fund so that should a coastal flood event occur in Vancouver, the City can properly document the event hazard, damages and losses. This potential dataset would be invaluable to future flood consequence and risk research in the City.

5. The City should consider collecting relevant asset information that would help with future risk assessments. Specifically, new building permits should record:

    a. First-floor elevations
    b. Construction type (wood, concrete, etc.)
    c. Presence/absence of a basement
    d. Any flood-protection measures

Additional recommendations regarding gaps in the approach Hazus takes in addressing infrastructure damage and losses, business interruption costs, uncertainty in social losses, and environmental losses can be found in **Annex F**.

10 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

10.1 SUMMARY AND CONCLUSIONS

1. Five Scenarios were developed that encompass possible future sea level rise (SLR) conditions to 2200 combined with design storm events:

    - Scenario 1, Year 2013, 0.0 m SLR, 1:500 year storm hazard
    - Scenario 2, Year 2100, 0.6 m SLR, 1:500 year storm hazard
    - Scenario 3, Year 2100, 1.0 m SLR, 1:500 year storm hazard
    - Scenario 4, Year 2100, 1.0 m SLR, 1:10,00 year storm hazard
    - Scenario 5, Year 2200, 2.0 m SLR, 1:10,000 year storm hazard

    The scenarios were developed in consultation with the City and the Technical Advisory Group (TAG).

2. A continuous simulation approach (joint probability) was taken to establish the return periods of ocean levels affected by meteorological and oceanographic conditions for each of the scenarios. This approach is more statistically defensible compared to the method recommended by the Provincial Guidelines (Ausenco Sandwell, 2011), without added conservatism. DFLs are 0.4 m lower, and FCLs are on average 0.6 m to 2.7 m lower (due mostly to wave effect), than obtained using the 2011 Provincial Guideline method.

3. Two-dimensional hydraulic modelling was carried out to understand flooding under each scenario in the overland areas. The ocean levels from the continuous simulation were used as the boundary conditions for the overland flood model. The flood-prone shoreline was divided into four modelling zones with similar exposure and characteristics. The detailed model mesh incorporated built environment (roads, buildings) and associated roughness in the urban environment. It could not, however, resolve flooding in subterranean or underground areas.

4. Modelled flood depths were mapped for each zone for each scenario. Key hazard areas include:

    - Zone 1 – Jericho Beach, Kitsilano Beach
    - Zone 2 – Granville Island, Southeast False Creek
    - Zone 3 – Second Beach

- Zone 4 – Deadman's Island, Coal Harbour, railyard along Waterfront Road (between Canada Place and Centerm), Port lands near Rogers St., Pacific Terminal, and between Cascadia Terminal and New Brighton Park.

5. Modelled flood levels were found to be relatively consistent across each zone for each scenario. When the 0.6 m freeboard was added to the future scenario levels (Scenario 2 to 5) the flood extents expanded, most noticeably in Zone 2's False Creek Flats area, where the boundary shifted east from Main Street to Clark Drive.

6. A wave effect boundary was delineated, seaward of which a wave effects allowance could be added to construction levels. Wave effects were found to be small in Zone 2, which includes False Creek. In Zone 1, the area is exposed to north-west winds and the wave effects are significant with hard-hit areas including Spanish Banks, Locarno and Jericho Beaches and Kitsilano Beach. In Zone 3, Second Beach is susceptible to larger wave effects as well as along the seawall. In Zone 4, the Inner Harbour is exposed to winds from both the north-west and north-east, so the wave effects were based on a combination of waves from the two directions.

7. Flood Construction Levels (FCLs) were set based on Scenario 3, which was chosen in consultation with the City and the TAG. Freeboard was added to Scenario 3 modelled flood levels to give an FCL of 4.6 m GD that was consistent across the four flood-prone zones. An additional 0.3 m wave effect allowance would be applied seaward of the wave boundary to form the FCL in this wave zone (or requirement for a site-specific study).

8. Under Scenario 3, areas within the City that are vulnerable during a coastal flood were assessed and hot spot maps produced. From an emergency management perspective, health-care facilities in the Downtown core will see an influx of patients. Emergency routes such as Main Street and Pacific Boulevard will be partially inundated. Important transportation hubs such as Waterfront Station could potentially be vulnerable. Current planned Gathering Areas in the Downtown core will have to be redefined as some will be flooded. Although most infrastructure is expected to be unaffected, aging infrastructure may be vulnerable. Port Metro Vancouver operations will be affected by inundation of lands along south shore of Burrard Inlet. Commercial services within the flood zone, as well as coastal recreation-oriented public spaces, will be impacted. Cultural and historic sites in Gastown and Chinatown will flood. Community services and housing centres in the Downtown Eastside, particularly between Carrall St. and Main St., as well as school and childcare spaces in the Olympic Village, International Village and near Terminal Avenue are vulnerable.

9. A stormwater assessment of the False Creek Flats area of Zone 2 was carried out for future scenarios. Stormwater modelling results indicated that a substantial decrease in the

capacity of the system can be expected with SLR, and without mitigation, flooding extents and depths (of the stormwater system) will increase significantly. The most effective solution to mitigating sea level backwater impacts is likely to be the addition of pumping capacity to convey flows over a floodwall at the system outlets. The pump station needed to provide this pumping capacity would be large, requiring a maximum pumping rate on the order of 10 m^3/s if a forebay volume of 12,500 cubic metres were provided.

10. Hazus modelling was undertaken as a way of quantifying damages for a consequence assessment for flood-prone areas in Vancouver. The Hazus modelling, although limited in scope relative to the larger scale of impacts expected from a flood event, is the best available tool for flood consequence assessment in Canada and does provide insight into expected damages and losses that might be experienced by the City. In particular, it shows that a coastal flood event in Vancouver will have a large impact on people, first and foremost, displacing thousands of families in the short term, and causing disruption to hundreds of families while their residences are cleaned and repaired post-disaster. The results also show that a number of industrial buildings would be impacted, particularly along the Fraser River. These sites would also incur significant losses of contents and inventory as a result of flooding.

10.2 RECOMMENDATIONS

1. Sea level rise estimates of 0.6 m and 1.0 m were used in the assessment for year 2100 conditions. These values fall at the lower and upper ends of the expected range of SLR experienced in Vancouver. The SLR of 1.0 m by 2100 is consistent with Provincial policy. However, there is still considerable uncertainty with SLR estimates and reliance on interpolation of simulation results, rather than detailed simulation of finer increments of sea level rise, is considered to be a reasonable and an appropriate approach for intermediate and long-range planning purposes. It is recommended that the City monitor changes in sea level rise estimates and adapt its flood management plans accordingly.

2. Whether or not the intensity of storms is changing in coastal BC is only beginning to emerge, and it is presently reasonable to conclude that no significant change is expected (Ausenco Sandwell, 2011a). Accordingly, potential future increases in storm frequency and intensity were not considered in this study. If future scientific findings show an increase in storm intensity with climate change, then it is likely that the storm surge component of the ocean level series could be amplified to reflect such impacts, and would need to be accounted for in updating the study, specifically the ocean water levels associated with return periods of interest to the City: 1:500 year and 1:10,000 year events.

3. The calibration and validation of the overland flood models relied on limited documentation of historic flood events. To provide better data, it is recommended that any future large floods be better documented. Some simple actions include collecting more photos showing flood conditions and flood limits, having the photographs time-stamped, and staking and surveying high water marks. For extreme events, it would also be useful to measure wave heights that occur in overland areas and flow velocities along roads or between buildings. Calibration and validation of the overland flood model can subsequently take place using the new data.

4. Considerable effort was spent on refining the DEM to create the bare-earth version by removing items such as temporary structures and fill and excavation areas, or incorporating items such as underpasses and areas below bridges. It is recommended that when the City obtains LiDAR next time, that it considers having this work done by the LiDAR provider, which would be more efficient and economical.

5. Many planned changes to roads and other infrastructure were included in the overland flood model, such as the Powell Street Overpass currently under construction, and modifications to Pacific Boulevard and Griffiths Way planned as part of the removal of the Georgia Viaduct. Others were not, such as the reconstruction of Stewart Street on the Port lands. The overland flood model should be updated to include any future development, particularly if large areas are filled close to or above the FCL. While these changes are not expected to change the FCL, there may be an effect on the extents of flooding and local depths and velocities.

6. Flooding of below-structure and below-ground infrastructure was not assessed or mapped as part of this study. Further assessment is warranted using estimated water levels near the entrance points, with particular attention paid to access and egress hazards.

7. It is recommended that the results of the study and mapping be used to support identification and development of mitigation and adaptation options, both structural and non-structural, for Phase 2 of the project.

8. With respect to areas within the City that are vulnerable during a coastal flood, emergency evacuation and planning for the False Creek and Inner Harbour areas should be reviewed by the City and Emergency Response personnel. Current planned Gathering Areas in the Downtown core will have to be redefined as some of them are subject to flooding.

9. Stormwater modelling results indicate that a substantial decrease in the capacity of the system can be expected with SLR. An increase in pumping capacity is recommended to mitigate sea level backwater impacts.

10. Whereas results from the Hazus modelling can be used as a basis for going forward with flood mitigation planning in Phase 2, they should be viewed at an aggregate, big-picture scale, for

relative comparisons of damage and not be used for detailed cost-benefit assessments at this time.

11. The City should create a fund, so that should a coastal flood event occur in Vancouver, the City can properly document the event hazard, damages and losses. This potential dataset would be invaluable to future flood consequence and risk research in the City in the longer term.

11 FUTURE INVESTIGATIONS

The Phase 1 study is based on presently available information and best practices. Phase 2, currently starting up, will develop structural and non-structural flood mitigation measures. As the project moves into Phase 2, there are further investigations that may be necessary and include:

1. Re-running the overland flood model to assess different structural mitigation requirements and options.
2. As mitigation and adaption options are developed, there may be an opportunity to continue to refine the Hazus inventory and model.
3. Adjust consequence and risk and assessments based on possible future population, development density, land-use change and economic values.

At this time, no changes or updates to the hazard modelling and assessment are recommended. However, these may need to be updated if significant storm events occur and better calibration and verification data is collected, or if there is evidence that increasing storminess is possibly affecting the hind-cast. Other possible investigations are mentioned in **Annexes B**, **C** and **D**.

Sea level rise assumptions may need to be adjusted based on updated observations and estimates. It may be possible to interpolate the changes based on the current modelling; otherwise, new hazard modelling may be required.

There may be future opportunities to update the Hazus model as the model is adapted to the Canadian context and as better stage-damage curves are developed or become available. Details on the various adaptations are discussed in **Annex F**.

It is difficult to project how the City's flood risks may change over time. As flood hazards and vulnerabilities evolve, the present study will form a baseline to which future conditions can be compared.

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13 Glossary

Chart Datum: the vertical datum to which nautical charts are referenced. In Canada, this corresponds to Lower Low Water Level Large Tide (LLWLT), or the lowest tide which on average occurs every year.

Deterministic: the absence of randomness in a system. For a given input, a deterministic system will always provide the same output.

Diurnal: occurring once per day. Similarly semi-diurnal indicates a process occurring twice per day.

El Niño-Southern Oscillation (ENSO): a pattern of climate variability predominantly affecting the tropical Pacific, though large events can have significant effect in the North Pacific. Events usually last 1-2 years and occur every 2-7 years. Like the PDO, the ENSO is indicated by sea surface temperatures with warm events resulting in increased sea level.

Freeboard: an additional elevation allowance in the specification of Flood Construction Level. It is intended to provide a measure of safety, accounting for uncertainties in the FCL calculation.

Geodetic Datum (GD): a horizontal and vertical reference for geodetic data. The vertical component of a geodetic datum usually approximates mean sea level.

Higher High Water Level Large Tide (HHWLT): the highest water level which on average happens every year.

Inverse Barometer Effect: an adjustment in sea level due to changes in barometric pressure at the water surface. An increase in barometric pressure of 1 mb corresponds to a fall in sea level of 0.01 m.

King Tide: is a non-scientific term used to describe especially large tides which occur only a few times a year.

Pacific Decadal Oscillation (PDO): a long lived pattern of Pacific climate variability. Typical events last for 20-30 years and are indicated by warm or cool sea surface temperatures. Warm events result in increased sea level, cool events results in reduced sea level.

Probabilistic: the presence of randomness in a system. For a given input, a probabilistic system will not always provide the same output, although, the output can be described by a probability distribution.

Relative sea level rise (RSLR): the combined effects of sea level rise and subsidence (uplift) which gives an apparent rate of sea level rise at a fixed location on the earth's surface.

Sea level rise (due to climate change): a slow increase in sea levels associated with the thermal expansion of warming seas and melting of major stores of land ice.

Static Water Level: the sum of the still water level and static wave setup.

Still Water Level: the water level in the absence of waves (effects include PDO/ENSO, astronomical tide, storm surge and wind setup).

Storm surge: an increase or decrease in sea level due to atmospheric pressure changes and large scale wind stress associated with a storm.

Subsidence/uplift: the vertical motion of the earth's surface relative to a fixed datum.

Tides: the rise and fall of the sea level, predominantly twice a day, due to the gravitational attraction of the sun, the moon and the earth.

Tidal residual: the difference between the measured water level and the predicted tides.

Total Water Level: the sum of the still water level, wave setup and wave runup.

Wave runup: the vertical extent of waves above static water level as they wash up the beach.

Wave setup: an increase in sea level shoreward on the wave breaking zone due to momentum transferred from breaking waves. The wave breaking process "pushes" water up the shore causing an increase in sea level. Wave setup has a static component which is a constant increase in water level and a dynamic component which oscillates and is sometimes known as "surf beat".

Wind setup: an increase or decrease in sea level caused by wind stresses on the surface of the water. On-shore winds blowing over shallow water "push" the water up the shoreline causing an increase in sea level.

Maps

ANNEX A

DATA SUMMARY

Annex B

Ocean Model Development

ANNEX C

WAVE MEASUREMENTS AND OCEAN MODEL VALIDATION

Annex D

Overland Model Development

ANNEX E

VULNERABILITY ASSESSMENT

ANNEX F

CONSEQUENCE ASSESSMENT