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Lower Mainland Flood Management Strategy – Analysis of Flood Scenarios

Final Report
May 2015
KWL Project No. 2038.008

Prepared for:

Fraser Basin Council

Contents

Tables

Appendices

Executive Summary

This project is part of a larger initiative to develop a Lower Mainland Flood Management Strategy. The Fraser Basin Council is facilitating this collaborative process, which includes 26 local governments, the provincial and federal governments and numerous other partners. Following consultation with a number of key stakeholder communities in 2013, it was identified that a collaborative approach will be most effective in addressing the current conditions and future impacts from flooding on a regional perspective.

Phase 1 comprises analysis, planning and consultation with the coordination and support of the Government of Canada, Provincial ministries, and 25 local governments within the Lower Mainland. Phase 2 will focus on development of options assessment and implementation.

Phase 1 of this Lower Mainland Flood Management Strategy is comprised of the following projects:

- Project 1: Analysis of Flood Scenarios;
- Project 2: Regional Vulnerability Assessment; and
- Project 3: Flood Protection, Policies and Plans.

This study focuses on Project 1 – Analysis of Flood Scenarios.

The study area extends from White Rock to Squamish and from Hope to Richmond, and includes regional organizations such as Metro Vancouver, the Fraser Valley Regional District and select provincial ministries. The primary hazards considered for this study were coastal and Fraser River flooding. Due to the large extent of the study area and the data collection effort required on a regional level analysis, this study focused primarily on the use of existing flood hazard information from studies, reports and models that were readily available. Gaps and transfer of pertinent information, data and findings was analysed.

Two coastal and two Fraser River flooding scenarios were identified to support the regional vulnerability assessment. Consultations were held with the Fraser Basin Councils' technical committee on February 11 and March 10, 2015 and the criteria for selection of flood scenarios and associated flood levels were agreed. The flood scenarios selected acknowledge the impacts from sea level rise, climate change and site specific uncertainties on flood levels.

The following flood scenarios are recommended for the purposes of the Lower Mainland Flood Management Strategy's regional vulnerability assessment.

Coastal Flood Scenarios

- 1-in-500 AEP still-water ocean state with current sea level; and
- 1-in-500 AEP still-water ocean state with 1 m sea level rise.

Fraser River Flood Scenarios

- High tide with current sea level and 1894 design flood conditions in Fraser River; and
- High tide with 1 m sea level rise and "moderate" climate change for 1-in-500 AEP freshet flow conditions in Fraser River.

Coastal and Fraser River flood levels were determined for the selected flooding scenarios for individual communities from White Rock to Squamish and are presented in this report. Flood levels were mapped and a standalone GIS Portal with salient information was developed. Key gaps in existing data and studies in conjunction with the regional nature of this study were reviewed.

Some of the key conclusions and recommendations relevant for this study are provided below.

The primary objective of the Lower Mainland Flood Management Strategy Project – Analysis of Flood Scenarios is to support Project 2 of Phase 1 – Regional Vulnerability Assessment and should not be used for design of flood protection measures (i.e., Dike Design, Flood Protection).

The simplified site specific joint probability analysis conducted in this study highlights the importance of the effect of local conditions on flood levels. As well, there are a number of gaps in the current understanding of Canadian Hydrographic Service (CHS) data, local conditions such as subsidence, datum adjustments, and wave generation. These gaps also explain the uncertainties in the final flood level estimates.

Variations in flood level estimates due to local conditions may affect flood protection design, i.e., dike design, but are unlikely to impact the regional scale vulnerability assessment significantly. Therefore, a uniform geodetic coastal water surface elevation was selected for all locations, incorporating an acceptable allowance to address uncertainties (Table 3-4).

It is recommended that policy and design decisions from individual communities consider separate site specific analysis incorporating the combined effects of all processes to establish an appropriate level of safety for flood protection design studies. This may include evaluation of different approaches (i.e., combined, joint probability analysis, hindcast) for flood level estimates.

In addition to impacts from the Fraser River flooding, communities may experience catastrophic consequences from flooding from local rivers and creeks, including debris flooding and urban flooding due to ineffective drainage infrastructure. The consequences from these additional sources of flooding are not addressed for this regional study, but are recommended for future site specific flood risk assessment by individual communities for effective flood protection.

1. Introduction

The following key objectives were considered for this study:

- Review existing reports, and technical studies regarding coastal flood risks for communities and infrastructure in Lower Mainland, considering sea level rise and coastal storm conditions;
- Review existing reports, and technical studies regarding Fraser River flooding, considering climate change impacts on the Fraser River flood levels in the Lower Mainland;
- Define two coastal and two Fraser River flood scenarios that include sea level rise, and climate change impacts;
- Define coastal and Fraser River flood levels for the selected flood scenarios based on existing modelled outputs and separate joint probability assessment, where applicable to support a Regional Vulnerability Assessment; and
- Identify gaps in data and studies available for coastal and Fraser River flooding for the study area within the associated scope of works considered, and comment on joint probability assessment for coastal flood scenarios.

The most relevant reports, studies and models reviewed for this study were obtained from Fraser Basin Council, as detailed below:

- Lower Fraser River Hydraulic Model, Fraser Basin Council, NHC, Triton, December 2006;
- Fraser River Hydraulic Model Update, BCMoE, NHC, March 2008;
- Comprehensive Review of Fraser River at Hope – Flood Hydrology and Flows – Scoping Study, BCMoE, NHC, October 2008;
- Fraser River Design Flood Level Update – Hope to Mission, MFLNRO, March 2014;
- Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios, MFLNRO, NHC, May 2014;
- City of Vancouver, Coastal Flood Risk Assessment –Final Report NHC, December 2014;
- Serpentine, Nicomekl & Campbell Rivers - Climate Change Floodplain Review, City of Surrey, NHC, December 2012;
- City of Surrey, 2014. Serpentine & Nicomekl Rivers - Climate Change Floodplain Review – Phase 2 – Draft Report. Prepared by NHC (Northwest Hydraulic Consultants);
- Creek Hydrology, Floodplain Mapping and Bridge Hydraulic Assessment, (Seymour River, Lynn Creek, Mosquito Creek, and Mackay Creek), City of North Vancouver, KWL, 2012;
- National Floodplain Mapping Assessment - Final Report, Public Safety Canada, MMM, Matrix, June 2014;
- City of Coquitlam, KWL, Coquitlam River Flood Assessment, 2014; and
- District of Squamish – IFHMP Draft background report, KWL, 2015.

2. Selection of Flood Scenarios

The following assumptions were applied for selection of the flood scenarios:

- Allow for 1 m of Sea Level Rise (SLR) by year 2100 and 2 m SLR by year 2200 (Ausenco Sandwell, 2011c). This study has adopted the Province's climate change recommendation with an allowance of 1 m of Sea Level Rise (SLR) by year 2100; and
- For combining Fraser River and ocean conditions, the appropriate flood scenarios were analyzed on a site specific basis.

The various types of interaction of the Fraser River and coastal conditions were reviewed in order to establish the criteria for selection of flood scenarios. For this purpose, the coastal and river flood hazard interactions were generalized into the following categories as described below.

Coastal Hazards combined with Small Streams

For the coastal communities, the interaction of the coastal flooding can be combined with small streams. For example, the City of Vancouver (CoV, 2014) study assumed a 1-in-500-year AEP for the coastal hazard and 1-in-25-year AEP for streams. In these situations, the interaction of the coastal conditions and the relevant flows on small streams is not considered complex.

Coastal Hazards combined with Large Rivers

A flood hazard from this type of interaction can be characterized by two possible combinations as described below:

- High tide coastal hazard with a combined AEP River flood; and
- AEP coastal hazard with a combined AEP River flood, e.g., City of North Vancouver, 2012.

The interaction between the Fraser River and coastal hazard falls into this category. Key Fraser River flood scenarios are a freshet flow condition combined with high tide or a winter coastal conditions combined with a lower Fraser River flow.

River Interactions

For the study extent, a possible flood hazard can be defined by the interaction where the lower reaches of Fraser River tributaries are affected by backwater from the Fraser River (e.g., Coquitlam River, Pitt River, Vedder River). The flood hazards in this interaction can be characterized in two combinations as below:

1. Fraser River freshet water levels and typical tributary summer flows; and
2. Appropriate Fraser River winter water levels and 1-in-200-year AEP tributary flows.

Complex Interactions

Complex interactions between the coastal and river hazard require a joint probability analysis between river and coastal flood frequencies. The analysis of this interaction will produce a "true" combined AEP for the interaction between ocean and river peak flows. The City of Surrey Serpentine/Nicomekl study approach acknowledges this interaction. It is our opinion that such an analysis is unlikely to be required at other locations, however, must be assessed based on needs and local conditions.

- Due to the regional nature of the Lower Mainland Flood Management Strategy, coastal and river flooding are assessed independently. The primary impact from river flooding is considered to be from the Fraser River, so other river flood hazards and their interactions with coastal hazard were not considered.

The key criteria for selection of the flood scenarios include:

- Characterize flood vulnerability and consequences on a regional scale to be used for long-term planning and for an approximate damage assessment.
- Year 2100 is considered a reasonable planning horizon. This was considered a reasonable planning horizon given the typical lifespan for new buildings and infrastructure.
- With the exception of the Fraser River, other river flood hazards will not be included.
- Coastal flood hazards will be assessed for coastal communities on a site specific basis using a separate simplified joint probability approach, whilst utilizing up to date information from existing studies.
- Where flood scenarios have already been developed, these would be assessed for extrapolation to other locations, based on its suitability.
- The suggested 1-in-350-year AEP design floodplain mapping standards in the 2014 Public Safety Canada's National Floodplain Mapping study may not be entirely appropriate for the purpose of this study. The current Fraser River design flood is set to an approximately 1-in-500-year AEP and some local communities have adopted the 1-in-500-year AEP combined with estimated SLR standards for flood protection (e.g., City of Vancouver).
- The range of scenarios should acknowledge the difficulty of attaining future flood mitigation goals, and must be realistic.
- While the 1-in-500-year AEP is a larger event than normally considered in the province, it reflects a growing awareness of the societal and economic values of flood damage and the need to provide higher levels of protection, especially throughout parts of the Lower Mainland.

Based on the above criteria, the following flood scenarios are recommended.

Coastal Flood Scenarios

1. 1-in-500-year AEP still-water ocean state[1] with current sea level; and
2. 1-in-500-year AEP still-water ocean state with 1 m sea level rise.

Fraser River Flood Scenarios

1. High tide with current sea level and 1894 design flood conditions in the Fraser River; and
2. High tide with 1 m sea level rise and "moderate" climate change, and 1-in-500-year AEP freshet flow conditions in the Fraser River.

The following sections describe the assumptions and methodology adopted for determining the coastal and Fraser River flood levels for the above selected flood scenarios.

[1] For this flood scenarios analysis, still-water ocean state is described as the ocean level without wave effects but includes tide, external surge, and sea level rise components.

3. Coastal Flood Scenarios

Coastal floods typically occur when external storm surges combine with the highest tides of the year during the winter storm season. As part of this regional study, coastal communities from White Rock to Squamish were assessed to determine coastal flood levels for the selected scenarios. This study has adopted the Province's climate change recommendation with an allowance of 1 m of Sea Level Rise (SLR) by year 2100.

It was acknowledged that a number of different combinations of coastal flood scenarios can produce damaging consequences. However, only two coastal flood scenarios were selected for this study that are considered suitable for the proposed regional vulnerability assessment. These include:

- 1-in-500 AEP still-water ocean state with current sea level; and
- 1-in-500 AEP still-water ocean state with 1 m sea level rise.

Previous Studies

The available past reports and associated models address coastal flooding for some specific coastal communities; however, they do not consider the entire extent of this study's region. The following key reports were found to be relevant for this study.

- BC MFLNRO (BC Ministry of Forests, Lands and Natural Resource Operations), 2014. Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios – Final Report;
- City of Surrey, 2012. Serpentine, Nicomekl & Campbell Rivers - Climate Change Floodplain Review. Prepared by NHC (Northwest Hydraulic Consultants);
- City of Surrey, 2014. Serpentine & Nicomekl Rivers - Climate Change Floodplain Review - Phase 2 – Draft Report. Prepared by NHC (Northwest Hydraulic Consultants);
- City of Vancouver Coastal Flood Risk Assessment – Draft Final Report. 2014. Prepared by NHC (Northwest Hydraulic Consultants); and
- District of Squamish – IFHMP Draft background Report. 2015. Prepared by KWL (Kerr Wood Leidal Associates Ltd.). District of Squamish.

The 2014 City of Vancouver's Coastal Flood Risk Assessment study has adopted a continuous simulation hindcasting approach to establish ocean levels affected by meteorological and oceanographic conditions. The approach incorporates a hind-cast of 50+ years of data that considers individual coastal components that affect static water level; tides, storm surge, local wind setup and wave setup were analyzed. A separate site specific wave overland model was completed to incorporate wave run-up, and estimated flood depths and velocities for future climate change scenarios. The primary purpose of this approach was to evaluate flood risk and assist with future flood protection strategies for the City.

The BC MFLNRO's 2014 *Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios* report address a number of different flood scenario combinations including climate change and sea level rise. However, it is primarily a Fraser River hydraulic assessment report and is not suitable to establish coastal flood levels for individual coastal communities.

The 2014 City of Surrey Serpentine & Nicomekl Rivers - Climate Change Floodplain Review - Phase 2 Draft Report addresses the combined effects of coastal components to establish flood levels, through a continuous simulation approach where long-term (50+ years) simulations were conducted of the system's hydraulic performance. The simulated annual peak floodplain water levels were subject to conventional frequency analysis. The approach adopted the following assumptions (NHC, 2014):

- The joint occurrence of extreme sea levels and severe rainfall contained in the historic record will be maintained in the future; and
- Future sea level time series can be adequately constructed by simply increasing all water levels by a uniform amount and scaling storm surges contained in the historic record.

A site specific continuous simulation hindcasting approach incorporating all coastal components is considered statistically defensible and reduces the conservatism inherent in the 2011 Provincial method, but requires extensive resources and modeling. This was beyond the scope of the study considering the large extent of the study area and regional nature of the Lower Mainland Flood Management Strategy.

Local conditions including shoreline geometry, depth, and direction impact site specific ocean levels. Extrapolation of site specific findings from one coastal community to a number of different local conditions may provide unrealistic values. For this purpose, a separate simplified Joint Probability Analysis (JPA) of tide and external surge was applied using 10 relevant CHS tide stations extending from Squamish to White Rock, to evaluate coastal flood levels for the selected flood scenarios incorporating tidal prediction and storm surge. This method is similar to KWL's approach adopted for District of Squamish's IFHMP Background Study, 2014.

3.1 Coastal Flood Levels

The two main components that affect the coastal flood levels include:

- Still-water level, which includes tide, external surge, sea level rise; and
- Wave effects.

The key components and associated processes that impact coastal flood levels are described below.

3.1.1 Astronomical Tide

Astronomic tide is the regular and predictable variation in water levels caused by the gravitational interactions of the Earth, Sun, and Moon. The highest tides, commonly referred to as "King Tides" occur when the sun and moon are aligned and the moon is at its closest point of approach to the earth. Tides vary with the fortnightly, seasonal, and 18.6-year lunar cycles. Each 18.6 year cycle is referred to as a "tidal epoch", usually rounded to 19 years for convenience. The highest tides of each year typically occur in the winter around the New Year.

The Canadian Hydrographic Service (CHS) regularly calculates tide predictions for several tide stations on the BC coast. For this study, several decades of predicted tide data was obtained from CHS incorporating latest tidal constituents for the following 10 Stations covering periods 1914 to 2014. These stations were chosen as they in general encompass the geographic extent of the coastal communities considered for this study.

1. Point Atkinson (CHS Station #7795);
2. Vancouver (CHS Station #7735);
3. Deep Cove (CHS Station #7765);
4. Port Moody (CHS Station #7755);
5. False Creek (CHS Station #7710);
6. Sand Heads (CHS Station #7594);
7. Tsawwassen (CHS Station #7590);
8. White Rock (CHS Station #7577);
9. Crescent Beach (CHS Station #7579); and
10. Squamish (CHS Station #7811).

The predictions cover the periods 1914 to 2014, and include hourly high/low data. It is understood that CHS review of the tidal constituents for some stations is ongoing, and it is possible to witness further adjustments in the future resulting in changes to predicted values. The most relevant and suitable long-term gauging station is located at Point Atkinson (#7795) in West Vancouver.

3.1.2 External Surge – Residual Water Levels

Water levels along BC's coast are affected by offshore ocean-scale processes in the Pacific Ocean basin and includes processes such as atmospheric pressure, wind, wave momentum, and ocean currents, oscillations and temperature. Together, these conditions explain the majority of observed differences between measured water levels and predicted tides (Ausenco Sandwell, 2011a). These differences are often referred to as Residual Water Levels (RWLs).

Residual water levels exhibit typical seasonal (summer/winter) and annual patterns. The largest RWL recorded at Point Atkinson was 1.03 m in March 1999 (Tinis, 2013). Provincial guidelines prepared by Ausenco Sandwell (2011b) recommend applying a single frequency-magnitude relationship for external surge throughout the West Coast, Juan de Fuca Strait and Strait of Georgia. Further, there is presently no evidence to suggest that the frequency or magnitude of RWL events will change significantly as a result of climate change (Ausenco Sandwell, 2011c).

In many situations, the 50+ years of reliable residual water level data available for the CHS station at Point Atkinson (#7795) would be considered an acceptable record for engineering analysis. It is possible that continued data collection at Point Atkinson could reduce the uncertainty associated with extreme value extrapolation of that record over time. In addition, the suitability of Point Atkinson as a reference station for Howe Sound is well established (e.g., Thomson, 1981). Moreover, several recent coastal engineering studies in the region i.e., City of Vancouver (CoV, 2014); EBA, 2010; Tetra Tech EBA, 2014, and the lower Fraser River (BC MFLNRO, 2014) have chosen to rely on Point Atkinson's record data.

3.1.3 Joint Probability Analysis

Joint probability analysis involves a statistical or empirical recombination of the full range of independent tide and surge components.

Review of Acceptable Methods for Estimating Coastal Flood Levels

In May 2013, MFLNRO released a "Consultation Draft Amendment" that proposes revisions to the FHALUMG (Flood Hazard Area Land Use Management Guidelines). Subsequently, a coordinated response from a group of experienced practitioners including comments and feedback on the Draft Amendment was provided to the BC Ministry of Environment (KWL, 2014) and a copy of this response is included in Appendix B of this report. A number of relevant comments and recommendations from this response were found to be useful for understanding the implications of various methods for evaluating coastal flood levels and therefore warrants a discussion for this study.

The approaches reviewed comprise The "Combined Approach" which estimates tide and surge independently and combines them additively, while the "Joint Probability Analysis" (JPA) approach examines statistical combinations of the two processes. Other methods include statistical frequency analysis of extreme water levels and "hindcasting" using a continuous-simulation wind wave model. As part of this response, KWL conducted a comparison of the flood level estimates between the "Combined approach" and "Joint Probability Analysis" adopted for the 2014 IFHMP Squamish background Study. The difference was found to be relatively modest at the 200-year return period but increased as events become more extreme; this explains the deviation of the results from the two approaches.

Joint Probability Analysis (JPA) can be comparable to an extreme-value frequency analysis of a long and reliable series of observed water levels. JPA is only viable where locally-representative, reliable observed water level data are available over a sufficiently long period of record. The decision to adopt this method lies with the local jurisdictions based on the level of detail required for flood analysis.

KWL understands that the 2014 City of Vancouver Coastal Flood Risk Assessment has adopted a "hindcasting" using a continuous simulation of coastal component that include tide, surge, wind, and wave effects. The hindcasting approach explicitly estimates Total Water Level through incorporation of the coastal components, thereby avoiding the potentially conservative combination of a return period flood and the return period design wave.

Table 3-1 presents the level of effort and probable outcomes from the approaches described above. (Source: 2014, KWL coordinated response to draft amendment FHALUMG)

Table 3-1: Methods for Evaluation of Coastal Flood Levels

Method	Effort / Data Requirements	Resulting Inaccuracy
Combined Approach	Lowest	Highest
Joint Probability Analysis (also Statistical Frequency Analysis where observed data permit)	↓	↑
Hindcasting Analysis	Highest	Lowest

Given the extent and regional nature of the proposed Lower Mainland Flood Management Strategy and the extensive resources required to develop static water levels from a hind-casting analysis (e.g., CoV, 2014) for all coastal communities within this study extent, a simpler approach was adopted based on incremental probabilities that produces comparable results. This method is similar to KWL's approach adopted for District of Squamish's IFHMP background study, 2014. No special software was required for this analysis, and all relevant data was obtained free of charge from the Canadian Hydrographic Services (CHS).

Method Adopted for This Study

For this study, KWL adopted an external storm surge allowance based on data from Point Atkinson and completed a peaks-over-threshold frequency analysis of Residual Water Levels. This also provides a consistent approach with previous local studies as well as the provincial government's recent Fraser River study (BC MFLNRO, 2014). A Generalized Pareto Distribution was applied to 1-hour, 2-hour, 6-hour, 24-hour, and 120-hour average RWL exceedances for both storm season (October to March) and summer season (April to September).

The incremental joint probability analysis adopted in this study applies the following simplified assumptions:

- A 19-year time series of astronomic tide predictions (1996-2014) provides a complete description of tide behaviour;
- Site-specific application undertaken to evaluate any significant regional differences (e.g., due to basin effects of Burrard Inlet);
- External (i.e., regional) storm surge will be similar across the Lower Mainland coast and will not be affected by climate change;
- Storm surges have a typical duration ranging from one hour to several days and can be characterized by a set of water levels averaged over each duration;

- Surge behaviour is focussed within the October to March period and must be considered on a seasonal basis; and
- The combination of astronomic tide and external surge can explain most of the variation in regional still-water levels (excluding local effects).

For the combined approach, AEP values are determined by replacing complex statistical analysis with a set of simplifying assumptions. Key assumptions implicit in the final combined-approach AEP values include:

- Storm surges will follow the appropriate frequency-magnitude distribution, but only occur between mid-October and mid-January. No storm surges occur outside this period;
- Each storm surge lasts for six hours;
- Astronomic tides equivalent to HHWLT will occur three times in every two-week period during each year's storm surge season;
- Water levels equal to HHWLT last for 2.8 hours during each high tide;
- The longer duration of a typical storm surge (6 hours) relative to the assumed high tide (2.8 hours) means that the probability of a surge occurring at the same time as a high tide is twice that of the high tide occurring alone; and
- Extreme water levels cannot result from superimposing storm surge on tides lower than those described above.

Applying an incremental probability analysis with these simplifying assumptions generates a frequency-magnitude relationship for the combined effect of tide and external storm surge.

The following sections describe the individual components that influence the final water levels including their uncertainties.

3.1.4 Datum Adjustment

CHS publishes tide predictions and observed water levels in Chart Datum (CD), which varies for different stations associated with unique conversion values. The CHS chart datum is the plane of Lowest Normal Tide (LNT), which is equivalent to Lower Low Water, Large Tide for most modern charts (FOC, 2014). The appropriate conversion from CD to local geodetic benchmarks can vary over time in response to processes such as Sea Level Rise and local subsidence. Mean Water Levels (MWL, expressed in CD) are included in the CHS publications (e.g., FOC, 2014) and provide an approximate conversion between CD and geodetic datum.

For this study, site specific conversions were obtained directly from CHS. The resulting coastal water levels were compared for conversions from permanent benchmarks and its most recent GPS based Global Navigation Satellite System (GNSS) conversions. A number of different conversions were found to have been adopted in past studies, as detailed below.

- Triton (2006) study has adopted 3.04 m GSC conversion based on Point Atkinson;
- NHC (CoV, 2014) study assumed a Point Atkinson conversion of 3.1 m (MWL);
- It is necessary to acknowledge that mean water levels are site specific in nature and vary accordingly; and
- CHS have used Global Navigation Satellite System (GNSS) data to establish elevations at published benchmarks for some stations and suggests GPS conversions where appropriate (3.06 m at Point Atkinson).

It was identified during this study that not all of the Chart Datum conversions obtained from CHS considered stable reference benchmarks. We understand that CHS plans to address this deficiency by establishing new stations and other improvements. It is reasonable to assume that following a CHS update, the conversion of Chart Datum to geodetic datum will be revised.

Assuming the CHS's GNSS observation provides most recent conversion for some stations along with permanent benchmarks for other stations analyzed, they yield slightly different conversions that reflect the inconsistent local benchmark elevations. Relative changes in subsidence or destroyed permanent benchmarks could be some of the reasons attributable to this difference. However this will require further investigation on a site specific basis.

In order to compare water levels consistently between the stations analyzed in this study, it was considered reasonable to use same datum and origin. The only method that provided site-specific conversion data at all ten Stations was CHS GSC benchmarks. In general the following can be attributed to the differences encountered with the water level estimates.

- Uncertainties in origin of benchmark elevations (e.g., GNSS and GSC);
- Subsiding or unstable benchmarks; and
- Uncertainties in Tide prediction chart data available for different locations.

It is important to note that these discrepancies may be more relevant for design projects (e.g., flood protection structures) and do not significantly impact the outcome for the regional vulnerability assessment. The overall uncertainties from effects due to variations in local conditions between sites will be greater than only the datum discrepancies for this study, as described in sections below.

3.1.5 Local Effects

Local site-specific shoreline conditions affect coastal water levels. Key contributors comprise uplift and subsidence as well as wind setup and wave setup.

Uplift and subsidence

Tectonic changes comprising uplift and subsidence can lead to changes in ground elevations relative to MWL, affecting coastal water levels associated with the location. Uplift and subsidence rates for a number of locations in BC are documented in Appendix B of the provincial Sea Dike Guidelines (Ausenco Sandwell, 2011b), but may not be available for all sites and require long term monitoring. The 2008 DFO report, *An Examination of the Factors Affecting Relative and Absolute Sea Level in Coastal British Columbia*, by R. E. Thomson, B. D. Bornhold and S. Mazzotti, provides a broader-based examination of regional factors in the Lower Mainland, including effects of subsidence, tectonic uplift, etc. but was not reviewed for this study.

3.1.6 Waves

Wave effect is a local phenomenon that is generally dependent on near shore water levels, direction of waves, and composition and geometry of the shoreline. It can be reasonably expected that wave impacts on coastal water levels will increase with rising sea levels as water levels near the shore become deeper. Waves are generated by a sustained wind field over deep water, and has the potential for damaging consequences on coastal protection and coastal floodplain. Local conditions including water depth and shoreline geometry influence wave-run up and the depth of flooding inshore. So it can be assumed that the effect of waves on water levels varies locally and its contribution must be calculated explicitly for design purposes, i.e., flood protection design. The Cov, 2014 study and CoS, 2012, 2014 studies acknowledge this through the hind-cast approach, comprising site specific local conditions and wave models adopted.

Individual shoreline conditions of the coastal communities and local wave impacts on coastal water levels were not considered for this study, as these will require site specific modeling incorporating shoreline geometry. A suitable allowance of 0.6 m, addressing inconsistences in site specific data and overall uncertainty from local effects has been adopted.

3.1.7 Coastal Water Levels – Joint Probability of Tide + Surge

The results from this joint probability analysis are found to be within +/-2 to 5 cm of the coastal boundary condition values adopted by BC MFLNRO (2014) and other localised studies (i.e., CoV, 2014) for similar locations (i.e., Point Atkinson). However, larger discrepancies in water levels were identified for some of the other stations that require site specific allowances for uncertainties. The discrepancies can be particularly prominent in locations like Boundary Bay where the estimated wind setup can be up to 0.8 m for 200 year wind speeds and wave setup up to 0.4 m for similar conditions, for a total of approximately 1.2 m to address local conditions.

Table 3-2 below provides coastal flood levels and relevant chart datum values determined through joint probability assessment of tides and storm surge (excluding local effects from waves) conducted for a range of AEP scenarios including the 1-in-500 AEP flood scenario considered for this study.

Table 3-2: Coastal Flood Levels using Joint Probability (Tides + Storm Surge) – CHS Stations

CHS Station	Station No.	Datum	Benchmark ID	Return Period AEP Event						
				50	100	200	500	1000	5000	10000
Benchmark-GNSS										
Point Atkinson	7795	3.06	CHS GNSS	2.58	2.64	2.70	2.77	2.81	2.91	2.95
Vancouver	7735	3.00	CHS GNSS	2.65	2.71	2.77	2.84	2.88	2.98	3.02
Port Moody	7755	3.14	CHS GNSS	2.56	2.62	2.68	2.75	2.80	2.90	2.94
Tsawwassen	7590	3.01	CHS GNSS	2.35	2.41	2.46	2.53	2.58	2.68	2.71
Squamish	7810	3.21	M07C9001	2.42	2.48	2.54	2.61	2.66	2.76	2.80
Benchmark-GSC										
Point Atkinson	7795	3.04	213-J-2	2.60	2.66	2.72	2.79	2.83	2.93	2.97
Vancouver	7735	2.98	1J	2.67	2.73	2.79	2.86	2.90	3.00	3.04
Deep Cove	7765	3.07	10-1964	2.60	2.67	2.73	2.80	2.86	2.96	3.00
Port Moody	7755	3.06	25-1961	2.64	2.70	2.76	2.83	2.88	2.98	3.02
False Creek	7710	3.02	1236-J1974	2.59	2.66	2.72	2.79	2.85	2.95	2.99
Sand Heads	7594	3.26	brass plug	2.30	2.37	2.43	2.50	2.55	2.65	2.69
Tsawwassen	7590	2.99	77C010	2.37	2.43	2.48	2.55	2.60	2.70	2.73
White Rock	7577	2.74	18-J	2.48	2.55	2.60	2.67	2.72	2.83	2.87
Crescent Beach	7579	2.74	16-J	2.35	2.41	2.46	2.53	2.58	2.68	2.72
Squamish	7810	3.06	77HA891	2.57	2.63	2.69	2.76	2.81	2.91	2.95
Past Studies										
MFLNRO (NHC) 2014 Study	7795	3.10	NHC	2.59	2.65	2.70	2.76	2.79	2.87	2.90
Point Atkinson (NHC)	7795	3.10	NHC	2.54	2.60	2.66	2.73	2.77	2.87	2.91
Point Atkinson (Triton, 2006)	7795	3.04	Triton/NHC	2.60	2.66	2.72	2.79	2.83	2.93	2.97

CHS Station	Station No.	Datum	Benchmark ID	Return Period AEP Event						
				50	100	200	500	1000	5000	10000
CHS Mean Water Level										
Point Atkinson	7795	3.09	CHS	2.55	2.61	2.67	2.74	2.78	2.88	2.92
Vancouver	7735	3.06	CHS	2.59	2.65	2.71	2.78	2.82	2.92	2.96
Deep Cove	7765	2.99	CHS	2.68	2.75	2.81	2.88	2.94	3.04	3.08
Port Moody	7755	3.08	CHS	2.62	2.68	2.74	2.81	2.86	2.96	3.00
False Creek	7710	2.99	CHS	2.62	2.69	2.75	2.82	2.88	2.98	3.02
Sand Heads	7594	3.10	CHS	2.47	2.54	2.60	2.67	2.72	2.82	2.86
Tsawwassen	7590	2.96	CHS	2.40	2.46	2.51	2.58	2.63	2.73	2.76
White Rock	7577	2.80	CHS	2.42	2.49	2.54	2.61	2.66	2.77	2.81
Crescent Beach	7579	2.80	CHS	2.29	2.35	2.40	2.47	2.52	2.62	2.66
Squamish	7810	3.14	CHS	2.49	2.55	2.61	2.68	2.73	2.83	2.87
Chart Datum (pre-adjusted values)		**HHWLT**	**MWL**							
Point Atkinson	7795	4.99	3.09	5.64	5.70	5.76	5.83	5.87	5.97	6.01
Vancouver	7735	5.00	3.06	5.65	5.71	5.77	5.84	5.88	5.98	6.02
Deep Cove	7594	5.50	2.99	5.67	5.74	5.80	5.87	5.93	6.03	6.07
Port Moody	7577	5.06	3.08	5.70	5.76	5.82	5.89	5.94	6.04	6.08
False Creek	7590	4.98	2.99	5.61	5.68	5.74	5.81	5.87	5.97	6.01
Sand Heads	7755	4.92	3.10	5.56	5.63	5.69	5.76	5.81	5.91	5.95
Tsawwassen	7765	4.69	2.96	5.36	5.42	5.47	5.54	5.59	5.69	5.72
White Rock	7710	4.56	2.80	5.22	5.29	5.34	5.41	5.46	5.57	5.61
Crescent Beach	7579	4.43	2.80	5.09	5.15	5.20	5.27	5.32	5.42	5.46
Squamish	7810	4.99	3.14	5.63	5.69	5.75	5.82	5.87	5.97	6.01

Notes:

1. The coastal flood levels are based on geodetic datum and include chart datum conversion (but excludes site-specific assessment of wave setup and localized wind setup). Further allowances for wave effects, and uncertainties due to local conditions should be considered.
2. Wave setup and site-specific wind setup are not included as it requires site-specific local conditions analysis.

Table 3-3 below shows coastal flood levels relevant for individual coastal communities excluding local effects, i.e., wave allowance, determined based on the joint probability analysis of tide and storm surge conducted for this study.

Table 3-3: Coastal Flood Levels using Joint Probability (Tides + Storm Surge) – Communities

Community	1-in-500 AEP + 0 m SLR	1-in-500 AEP + 1 m SLR
	Present Day Coastal Flood Level, GD[1]	Year 2100 Coastal Flood Level, GD[1]
City of Vancouver	2.86	3.86
City of North Vancouver	2.79	3.79
City of Port Moody	2.83	3.83
City of Richmond	2.50	3.50
City of Surrey	2.53	3.53
City of White Rock	2.67	3.67
Corporation of Delta	2.55	3.55

Community	1-in-500 AEP + 0 m SLR	1-in-500 AEP + 1 m SLR
	Present Day Coastal Flood Level, GD[1]	**Year 2100 Coastal Flood Level, GD[1]**
District of Squamish	2.76	3.76
District of West Vancouver	2.79	3.79
Village of Belcarra	2.80	3.80
Village of Lions Bay	2.79	3.79
City of Burnaby	2.80	3.80

Notes:
1. The coastal flood levels are based on geodetic datum and include chart datum conversion (but excludes site-specific assessment of wave setup and localized wind setup). Further allowances for wave effects, and uncertainties due to local conditions should be considered.
2. Wave setup and site-specific wind setup are not included as it requires site-specific local conditions analysis.

3.1.8 Recommended Coastal Water Levels

The joint probability approach adopted for this study provided site specific coastal water levels. However, a number of gaps have been identified in the current understanding of CHS data, local conditions such as subsidence, datum adjustments, and wave generation. These gaps may also explain the uncertainties in the final water level estimates.

In order to address the discrepancies and associated uncertainties, the following two options were discussed for recommendation of coastal water levels, for the purposes of Regional Vulnerability Assessment:

- **Adopt site specific values:** Accept variations (including uncertainties) in water levels and associated data discrepancies between sites.
- **Adopt uniform value (selected):** Adopt a suitable uniform geodetic coastal water surface elevation based on the results from the analysis, for all locations, incorporating an acceptable allowance to address uncertainties.

Concurrent with the regional nature of this study, it was agreed with the FBC technical committee on March 10, 2015 that it is appropriate to adopt a uniform value for all locations assuming an allowance 0.6 m to address uncertainties in coastal water level estimates to incorporate local effects, i.e., wave allowance, subsidence and datum uncertainties. Therefore, the recommended flood levels for the two coastal flood scenarios for the purpose of regional vulnerability assessment, based on a consistent 2.8 m GD (i.e., Point Atkinson) are as below. The flood levels presented in this report will support the Project 2 of Phase 1 – Regional Vulnerability Assessment, and should not be used for design of flood protection measures, i.e., dike design and as flood construction levels (FCL).

Table 3-4: Recommended Coastal Flood Levels for Lower Mainland Flood Management Strategy

Coastal Flood Scenarios	
1-in-500 AEP + 0 m SLR	**1-in-500 AEP + 1 m SLR**
Present Day Coastal Flood Level, GD	**Year 2100 Coastal Flood Level, GD**
3.40	4.40

Notes:
1. The Coastal Flood Level represents an assumed allowance of 0.6 m to address uncertainties from local conditions, i.e., waves, datum adjustments, uplift, subsidence.
2. A uniform geodetic coastal water surface elevation for all locations was adopted.

4. Fraser River Flood Scenarios

Previous Studies

The two major floods with damaging consequences on the Lower Fraser River occurred in 1894 and 1948. The 1894 flood was adopted in general for defining flood protection standards in the region. A number of past studies have been completed specifically addressing the 1894 flood event and its potential estimated flows for establishing flood protection. This includes studies undertaken by Fraser Basin Board (1958); hydrometric and sediment studies in Lower Fraser River by Inland Waters Branch (1970); upstream storage studies conducted by Fraser River Joint Advisory Board (1976) and the comprehensive review of flood hydrology and flows on Fraser River at Hope (NHC, 2008). Since 1999, a number of hydraulic modelling investigations were commissioned by the Fraser Basin Council and Ministry of Environment, and comprises MIKE 11 hydrodynamic models for the Fraser River. The studies include the UMA, 1999 report extending between Laidlaw and Mission. Subsequent hydraulic modeling studies include the hydraulic modelling of the tidally influenced reach between Mission and the mouth of the Fraser River, (NHC, 2006). These upper and lower reaches of the Fraser River were integrated to form a combined Lower Fraser River model (NHC, 2008a) which has since been used as the freshet forecasting model. In order to reflect the changes in the river bathymetry due to the dynamic nature of the gravel reach on modelled water levels, a new upper model was developed (NHC, 2014). This model was eventually combined with the lower model (NHC, 2008a) for flood forecasting purposes. The most recent and relevant study that addresses climate change and tidal impacts on the Fraser River was undertaken by MFLNRO (NHC, 2014).

Flood Scenarios

Two Fraser River Flood Scenarios were considered for this analysis, as described below:

1. High tide with current sea level and 1894 design flood conditions in Fraser River; and
2. High tide with 1 m sea level rise and “moderate” climate change for 1-in-500-year AEP freshet flow conditions in Fraser River

Flood Levels Criteria

The following assumption and methodology was applied for determining Fraser River flood levels for the above two flood scenarios:

- With the exception of the Fraser River, other river flood hazards were not considered for deriving water levels for the above scenarios. It is assumed that a successive failure of existing flood protection will be considered to assess consequences from flooding, and that the primary impact from River flooding will be from the Fraser River.
- The *Fraser River Design Flood Level Update – Hope to Mission* (MFLNRO 2014) report and associated model provides the latest water levels for the 1894 design flood for the upper reach. At this time of study, although this model was known to have been run as a merged model including the lower reach (Mission to mouth of Fraser River), the lower model is currently being used for annual flood level forecasting purposes only with no immediate plans to update the design profile downstream of Mission.
- The *Fraser River Hydraulic Model Update* (NHC 2008) study and associated model was considered for defining the 1894 design flood profile for the lower model reach.
- The *Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios*, (MFLNRO, 2014) study addresses the climate change in Fraser River watershed and tidal impacts. The associated modeling considered 105 freshet profile scenarios and 35 winter profile scenarios.

This report was reviewed to obtain water levels for the year 2100 flood scenario combining climate change conditions and tidal conditions in the watershed. There was no design flood (1894) scenario combination modelled but includes the 1-in-500-year AEP flood scenario required for this study.

- The 1894 Fraser River design flood scenario assumes flows if 17,000 m^3/s at Hope and is considered slightly higher than the 1-in-500-year AEP flows for this location (NHC, 2008a).
- Moderate climate change conditions in the watershed affecting Fraser River flows for Year 2100, based on the PCIC recommendations (MoFLNRO, 2014) was adopted for this study.
- The 1-in-500 AEP Fraser River freshet historic flows of 16,500 m^3/s (present day condition) and with a 'moderate' climate change scenario of 19,900 cms (year 2100 condition) at Hope was assumed (MFLNRO, NHC, 2014). The 1-in-500 year AEP Fraser River freshet historic flows was found to be marginally lower than the 1894 flood flows estimated in previous studies (NHC, 2008) and the 1-in-500-year freshet flows with moderate climate change flows equates to an approximately 1-in-5,000-year freshet flows in present day scenario.
- Maximum water surface elevations for the above two flood scenarios were selected on a site specific basis. Municipal boundaries were used to reflect river reach extents and water levels were extracted from the MFLNRO study for upstream and downstream locations. The water levels are representative of the area and extent of the individual community. Some communities will experience both river and coastal flooding due to their locations.
- Likely gaps identified in the available Fraser River studies and models include the application of 1-Dimensional hydrodynamic models excluding dike overtopping and associated floodplain storage. A number of flow conveyance structures such as bridges and diversions might exhibit losses or upstream impacts based on current dike elevations and available storage which is not representative of the flood level calculations. Site specific flood risk assessments may require additional detailed modeling incorporating overtopping and dike breaches to establish flood depths and associated velocities accurately.

4.1 Fraser River Flood Levels

Table 4-1 below provides recommended Fraser River flood levels (freshet flood conditions) for individual communities within the study extent for all selected flood scenarios. **The flood levels presented in this report will support the Lower Mainland Flood Management Strategy's 'Regional Vulnerability Assessment' study, and should NOT be used for the purposes of planning policy and/or design of flood protection measures.**

Table 4-1: Recommended Fraser River Flood Levels for Lower Mainland Flood Management Strategy

Community	Fraser River Section	Chainage	Fraser River Design Flood (1894) + 0 m SLR (m)	1-in-500 AEP + Moderate Climate Change + 1 m SLR (m)
City of Vancouver	North arm	22157	2.57	3.77
	North arm	1238	1.56	2.89
City of Richmond/Sea Island	Middle Arm	14066	1.90	3.77
	North arm	9913	1.68	2.89
City of Richmond	Fraser	28761	3.14	3.77
	Fraser	9650	1.55	2.89
Delta	Fraser	31926	3.54	4.53
	Fraser	9650	1.55	2.89
City of Burnaby	Fraser River	28761	3.14	5.24

Community	Fraser River Section	Chainage	Fraser River Design Flood (1894) + 0 m SLR (m)	1-in-500 AEP + Moderate Climate Change + 1 m SLR (m)
	North arm	22157	2.57	3.77
City of New Westminster	Fraser	37528	4.22	5.24
	North arm	28761	3.14	3.77
City of Surrey	Barnston	6011	5.83	6.75
	Fraser	31926	3.54	4.53
City of Coquitlam	Fraser	42617	4.67	5.80
	Fraser	37528	4.22	5.24
City of Port Coquitlam	Fraser	46984	4.92	6.20
	Fraser	42617	4.67	5.80
District of Pitt Meadows	Fraser	53954	6.00	7.05
	Fraser	46984	4.92	6.20
District of Maple Ridge	Fraser	73842	7.90	8.91
	Fraser	53954	6.00	7.05
Langley	Fraser	70804	7.66	8.60
	Barnston	6011	5.83	6.75
Abbotsford	Fraser	100688	10.55	11.66
	Fraser	70804	7.66	8.60
Chilliwack	Fraser	129916	18.18	18.76
	Fraser	100688	10.55	11.66
District of Mission	Fraser	89601	9.44	10.62
	Fraser	73842	7.90	8.91
Fraser Valley District G	Fraser	113344	12.03	12.87
	Fraser	89601	9.44	10.62
Fraser Valley District C	Fraser	117465	13.68	14.39
	Fraser	113344	12.03	12.87
Fraser Valley District D	Fraser	144434	25.26	25.76
	Fraser	129916	18.18	18.76
Fraser Valley District B	Fraser	156778	32.98	33.64
	Fraser	144434	25.26	25.76
Kent	Fraser	153743	31.66	32.35
	Fraser	117465	13.68	14.39
Fraser Valley District A	Fraser	162143	36.80	37.88
	Fraser	153743	31.66	32.35
Hope	Fraser	167135	39.55	40.39
	Fraser	156778	32.98	33.64

Notes:
1. All Fraser River design flood levels are based on freshet flood conditions only.
2. The *Fraser River Design Flood Level Update – Hope to Mission* (MFLNRO 2014) report and associated model provides the latest water levels for the 1894 design flood for the upper reach.
3. The *Fraser River Hydraulic Model Update* (NHC 2008) study and associated model was considered for defining the 1894 design flood levels for the lower reach.
4. 1-in-500 AEP + Moderate Climate Change + 1 m SLR flood levels are based on results from the 2014 MFLNRO Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios study.

Mapping and GIS

Maps with flood levels comprising coastal and Fraser River flood levels for all selected flood scenarios was developed and is presented as Figure 1-3 in Appendix A. In addition, a standalone GIS Portal with salient information including flood levels, municipal boundaries, Fraser River reaches and dedicated secure access was developed for the purpose of this study. The primary framework and associated data for this portal will remain within the KWL's managed server. It is assumed at this stage that secure access and copyrights for project data used in this portal will reside with Fraser Basin Council for this project including discretionary dissemination of data for the period of Lower Mainland Flood Management Strategy as indicated by Fraser Basin Council, i.e., Phase 1 (2014-2015). Beyond this timeline, subject to FBC's approval KWL may maintain this GIS portal and associated data or transfer to FBC's own server for a nominal fee.

5. Conclusions and Recommendations

Conclusions

The primary objective of the Lower Mainland Flood Management Strategy Project – Analysis of Flood Scenarios is to support Project 2 of Phase 1 – Regional Vulnerability Assessment, and the flood levels presented in this report should not be used for design of flood protection measures (i.e., Dike Design, Flood Protection).

Due to the regional nature of the Lower Mainland Strategy, two coastal and two Fraser River flood scenarios were considered.

There were no relevant past studies completed that specifically addressed increases in coastal storm intensity resulting from climate change for the extent of this study area.

Most coastal flood studies provided a 1-in-200-year AEP coastal flood level and do not investigate the specific AEP scenarios considered for the entire study area. The CoV 2014, MFLNRO and Squamish IFHMP studies have addressed lower flood frequencies, i.e., 1-in-500-year AEP, on a site-specific basis.

Local conditions including shoreline geometry, depth, and direction impact site specific ocean levels. Extrapolation of site specific findings from one coastal community to a number of different local conditions may provide unrealistic values. A site specific continuous simulation hindcasting approach incorporating all coastal components (CoV & City of Surrey, 2014) is considered statistically defensible and reduces the conservatism inherent in the 2011 Provincial method. Such a site specific analysis considering the large extent of the study area and regional nature of the Lower Mainland Flood Management Strategy, would require significant analysis and reliable long-term wind and water level data.

The simplified joint probability approach adopted for this study provided site specific coastal flood levels. However, a number of gaps have been identified in the current understanding of CHS data, local conditions such as subsidence, datum adjustments, and wave generation. These gaps also explain the uncertainties in the final flood level estimates.

Variations in flood level estimates due to local conditions may affect flood protection design i.e. dike design, but are unlikely to impact the regional scale vulnerability assessment significantly. Therefore, a uniform geodetic coastal water surface elevation, for all locations, incorporating an acceptable allowance to address uncertainties was selected (Table 3-4).

The *Fraser River Design Flood Level Update – Hope to Mission* (BC MFLNRO, 2014) report and associated model is relevant for determining the 1894 design flood for the upper reach. The *Fraser River Hydraulic Model Update* (NHC 2008) study and associated model comprise the 1894 design flood profile for the lower reach. Moderate climate change conditions in the watershed affecting Fraser River flows towards the end of the century (MFLNRO, 2014) were adopted for this study.

Although a number of different previous studies address Fraser River flooding in the region, only the MFLNRO study on the Fraser River addressed all possible AEP flood scenarios with climate change and sea level rise combinations considered for this study. The 2014 MFLNRO *Simulating the Effects of Sea Level Rise and Climate Change on Fraser River Flood Scenarios* study provided relevant flood levels for the year 2100 flood scenario combining increased flows from climate change in the Fraser River and Sea Level Rise.

Recommendations

KWL identified a number of recommendations from the flood scenario analysis, which include:

- The simplified site specific joint probability analysis conducted in this study highlights the importance of the effect of local conditions on coastal flood levels. It is recommended that the Fraser Basin Council or its Project 2 consultant liaise with CHS to obtain further clarification on the discrepancies in current data, i.e., chart datum, local geodetic benchmarks, subsidence and uplift etc. and if new information can be provided prior to completion of the Phase 2 (i.e., regional vulnerability assessment). The new information may then be applied to improve flood level estimates to enhance the predicted outcome of the regional vulnerability assessment.
- Assessing coastal flood levels in areas protected by sea dikes can be complex, in particular where overtopping rates may vary locally and act as a secondary source of flooding. Another situation can include areas enclosed or "bathtub" areas where coastal flood protection performs well; dikes retain water from an upstream river dike breach until it begins to spill out over the sea dikes. This condition does not necessarily apply for this study where successive dike failure scenarios may be considered for assessing flooding consequences on a regional scale. However, it is recommended that the secondary sources of flooding be assessed on a site-specific basis by individual jurisdictions.
- It is recommended that local authorities adopt a higher target for flood protection where justified by benefit-cost analysis or other forms of Quantitative Risk Assessment.
- The current Fraser River models available for the study region comprise 1-Dimensional hydrodynamic models that exclude dike overtopping and associated floodplain storage. Site specific flood risk assessments may require additional detailed modeling incorporating dike overtopping and dike breaches to establish flood depths and associated velocities accurately. This could particularly be relevant for low floodplain areas and other specific dike reaches with low AEP standards of protection.
- In addition to impacts from the Fraser River flooding, a number of communities may experience catastrophic consequences from debris floods from local rivers and creeks, and overwhelming of drainage infrastructure in heavily urbanized areas. The consequences from these additional sources of flooding are not addressed for this regional study, but are recommended for future site specific flood risk assessment by individual communities for effective flood protection.
- It is recommended that policy and design decisions from individual communities must consider separate site specific analysis incorporating the combined effects of all processes to establish an appropriate level of safety for flood protection design studies. This may include evaluation of different approaches for flood level estimates that best meets their needs. Acceptable approaches could include the Combined Approach, JPA, and hindcasting. Statistical frequency analysis of observed water levels could be considered as an acceptable approach where the observed record of water levels is sufficiently long and reliable.

6. Report Submission

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Statement of Limitations

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Revision History

Revision #	Date	Status	Revision	Author
A	March 7, 2015	DRAFT	Draft Report for Fraser Basin Council	LF/DS
B	May 19, 2015	FINAL	Final Report for Fraser Basin Council	LF/DS

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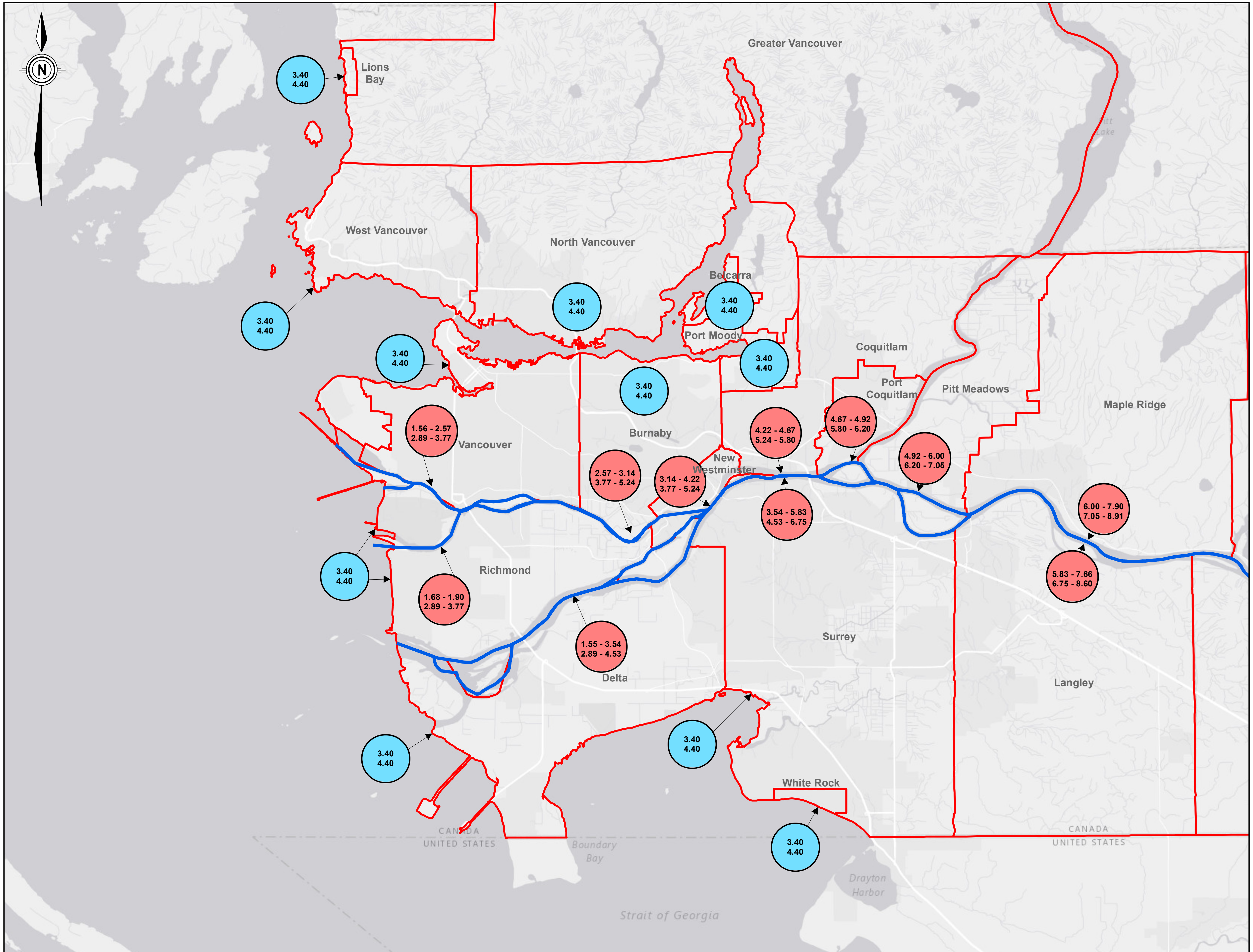
Appendix A

Flood Scenarios – Flood Levels



Fraser Basin Council

ANALYSIS OF FLOOD SCENARIOS

Legend

Stream Reach

Municipal Boundary

Coastal Flood Levels

- Value 1 → 1 in 500-yr AEP + 0m SLR
- Value 2 → 1 in 500-yr AEP + 1m SLR

Fraser River Water Levels

- Range 1 → Fraser River Design Flood (1894) + 0m SLR
- Range 2 → 1 in 500-yr AEP (moderate) + 1m SLR

Note: For Fraser River Flood Levels
Value 1 = Downstream
Value 2 = Upstream

Notes :

1. All Fraser River design flood levels are based on freshet flood conditions only.
2. All flood levels shown in geodetic datum.
3. Coastal flood levels include 0.6 m allowance to address uncertainties from local conditions i.e., waves, datum adjustments, uplift, subsidence.
4. The flood levels presented will support the Lower Mainland Flood Management Strategy's 'Regional Vulnerability Assessment' study, and should NOT be used for the purposes of planning policy and/or design of flood protection measures.

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Kilometers

Project No.	Date
2038-008	May 2015

Lower Mainland Flood Management Strategy
Flood Scenarios - Flood Levels

Figure 1

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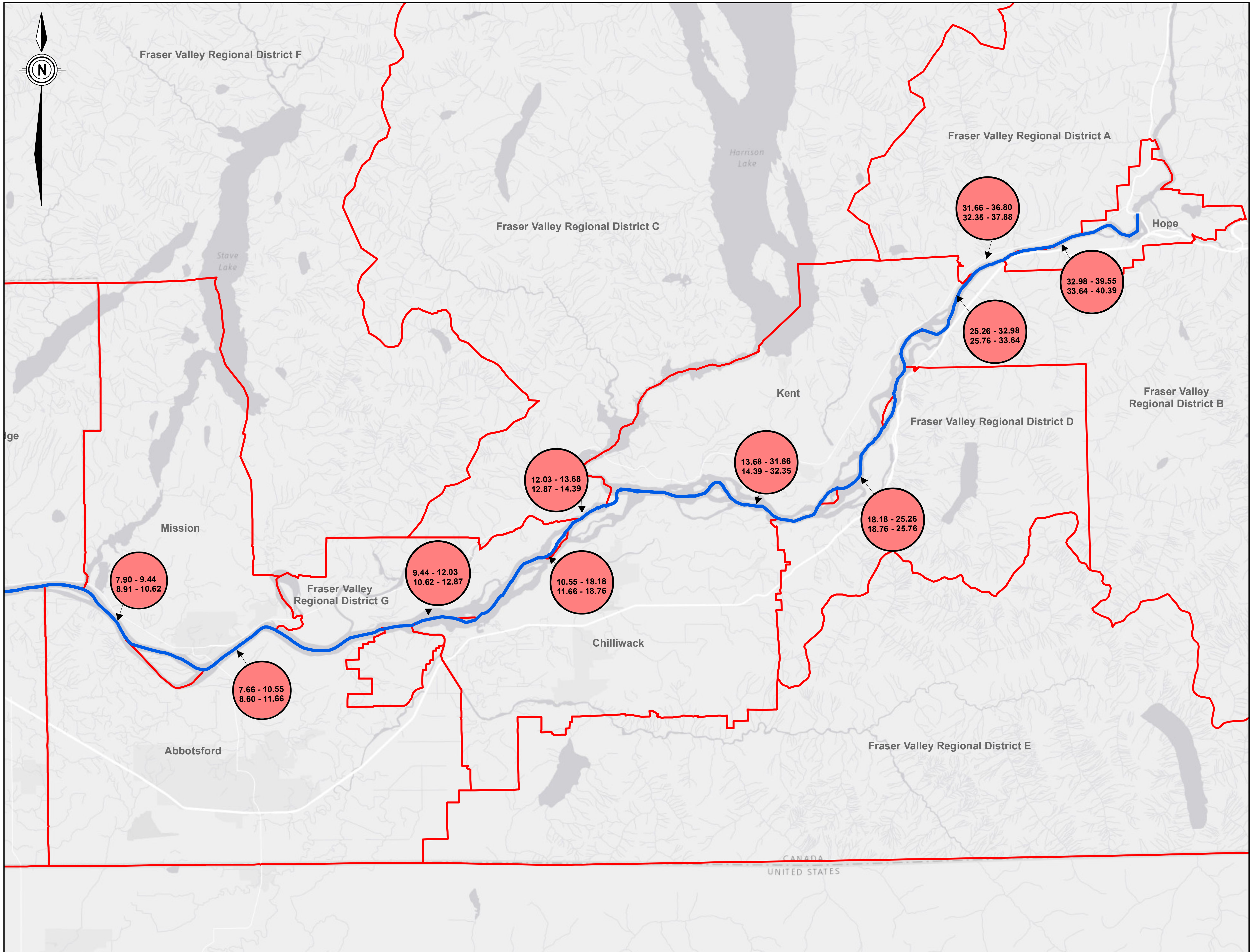
Author: DLenuzzi



Fraser Basin Council

ANALYSIS OF FLOOD SCENARIOS

Legend

Stream Reach

Municipal Boundary

Coastal Flood Levels

- Value 1 → 1 in 500-yr AEP + 0m SLR
- Value 2 → 1 in 500-yr AEP + 1m SLR

Fraser River Water Levels

- Range 1 → Fraser River Design Flood (1894) + 0m SLR
- Range 2 → 1 in 500-yr AEP (moderate) + 1m SLR

Note: For Fraser River Flood Levels
Value 1 = Downstream
Value 2 = Upstream

Notes :

1. All Fraser River design flood levels are based on freshet flood conditions only.
2. All flood levels shown in geodetic datum.
3. Coastal flood levels include 0.6 m allowance to address uncertainties from local conditions i.e., waves, datum adjustments, uplift, subsidence.
4. The flood levels presented will support the Lower Mainland Flood Management Strategy's 'Regional Vulnerability Assessment' study, and should NOT be used for the purposes of planning policy and/or design of flood protection measures.

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KERR WOOD LEIDAL
consulting engineers

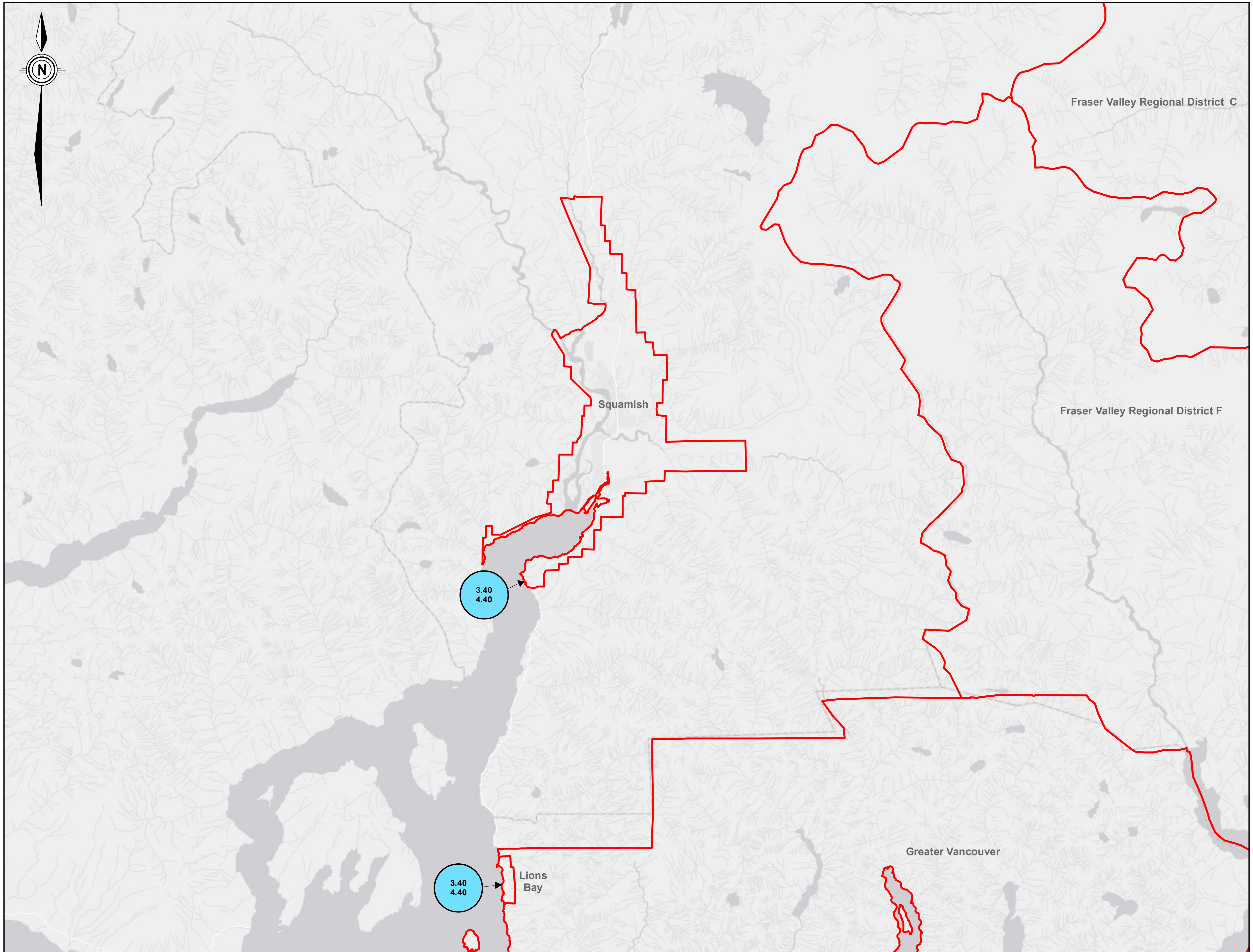
5 0 5
Kilometers

Project No.	Date
2038-008	May 2015

Lower Mainland Flood Management Strategy
Flood Scenarios - Flood Levels

Figure 2

Path: Q:\2000-2099\2038-008\430-GIS\MXD-RP\2038008_Flood_Scenarios_.mxd Date Saved: 5/19/2015 12:07:32 PM
Author: DLenuzzi



Fraser Basin Council

ANALYSIS OF FLOOD SCENARIOS

Legend

Stream Reach

Municipal Boundary

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Kilometers

Project No.	Date
2038-008	May 2015

Lower Mainland Flood Management Strategy
Flood Scenarios - Flood Levels

Figure 3

Path: Q:\2000-2099\2038-008\430-GIS\MXD-RP\2038008_Flood_Scenarios_.mxd Date Saved: 5/19/2015 12:07:32 PM
Author: DLenuzzi

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Appendix B

Draft Amendment to FHALUMG – Co-ordinated Response

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October 31, 2014

Ms. Tina Neale
Water Program Analyst
Water Protection and Sustainability Branch
Ministry of Environment
PO Box 9362 STN PROV GOVT
Victoria, BC V8W 9M2

Dear Ms. Neale:

RE: DRAFT AMENDMENT TO FLOOD HAZARD AREA LAND USE MANAGEMENT GUIDELINES
Co-ordinated Response from KWL Professionals
Our File 0999.625L

In 2004, the BC Ministry of Water, Land and Air Protection (now Ministry of Forests, Lands and Natural Resource Operations, MFLNRO) released the Flood Hazard Area Land Use Management Guidelines (FHALUMG). Since that time, the FHALUMG have played a key role in defining industry best practice for floodplain planning and development in BC.

In May 2013, MFLNRO released a "Consultation Draft Amendment" (Draft Amendment) that proposes revisions to the FHALUMG. The Draft Amendment incorporates Sea Level Rise (SLR) considerations into Sections 3.5 (dealing with "The Sea") and 3.6 (addressing areas protected by standard dikes). The Draft Amendment draws on a series of 2011 documents prepared by Ausenco Sandwell as well as MFLNRO's internal expertise. MFLNRO is currently soliciting comments and feedback on the Draft Amendment from BC's flood hazard management community.

This co-ordinated response is intended to facilitate MFLNRO's internal review and to underscore the consensus opinion of a group of experienced practitioners at KWL. Professionals participating in this co-ordinated response include:

- Mike Currie, M.Eng., P.Eng., FEC
- David Sellars, M.Sc., P.Eng.
- Dave Murray, P.Eng., A.Sc.T., CPESC
- Colin Kristiansen, MBA, P.Eng.
- Eric Morris, M.A.Sc., P.Eng.
- Erica Ellis, M.Sc., P.Geo.
- Craig Sutherland, M.Sc., P.Eng.
- David Roche, M.A.Sc., P.Eng.

All of the individuals listed above have contributed to this response, and this letter is submitted on their behalf.

APEGBC Flood Hazard Guidelines

In 2012, the Association of Professional Engineers and Geoscientists of BC (APEGBC) released a document entitled "Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC". These guidelines are a valuable tool for engineering and geoscience practitioners, and generally complement the FHALUMG in many areas. A key focus of the APEGBC guidelines is a move towards risk-based decision-making.

APEGBC's 2012 guidelines are largely silent on the subject of coastal flood hazards. Similarly, the FHALUMG are largely silent on the potential for a risk-based approach, following more the traditional hazard-based approach of flood hazard management.

We hope that MFLNRO will work with APEGBC to harmonize the revised FHALUMG with an update to the APEGBC guidelines that more comprehensively addresses coastal flood hazards.

Standard of Protection

We welcome MFLNRO's efforts to incorporate reasonable and appropriate SLR provisions into a best-practices vision for the industry. The Draft Amendment appears to recognize that the level of protection prescribed by the 2011 Ausenco Sandwell reports may prove to be unrealistic for many jurisdictions. As an alternative, the Draft Amendment proposes a 200-year return period (1 in 200 Annual Exceedance Probability or AEP) Designated Flood Level (DFL) combination of astronomic tide and external storm surge, plus concurrent allowances for local wind and wave effects.

In our opinion, it would be preferable to express the minimum target for protection in terms of Total Water Level (e.g., the critical combination of tide, storm surge, wind setup, and wave effects). We recommend that the revised FHALUMG specify Total Water Level as the intended target, but also advise readers that direct calculation of Total Water Level is technically complex and may be beyond the resources of many local authorities. Simple addition of concurrent local wind and wave effects to the DFL is an appropriate alternative to directly estimating Total Water Level, subject to the caveats discussed below.

A 200-year return period event is a reasonable minimum target for coastal flood hazard protection in BC given the current state of coastal flood hazard management in BC, the uncertainty associated with SLR estimates, and the corresponding state of practice for flood analysis on rivers. A more conservative minimum level of protection (i.e., greater than 1 in 200) may be appropriate in some circumstances. Some considerations for selecting a level of protection are outlined below:

- The Draft Amendment requires that the DFL be defined for the *end* of the local authority's planning horizon. The level of protection provided by specifying a design event at the end of the SLR planning horizon is more conservative than the nominal design event suggests, since the event AEP only approaches the intended threshold during the final years of the analysis. The total probability of exceeding the 200-year return period *future* DFL is much lower than the well-known 39% chance of exceeding a "stationary" 200-year return period event over a 100 year period.

- Many BC communities are subject to concurrent river and coastal flood hazards. For situations where these two processes result in comparable consequences, applying disparate minimum standards of protection could negatively impact a local authority's ability to optimize risk mitigation decisions.

- Appendix D of Ausenco Sandwell's 2011 Sea Dike Guidelines provides a brief analysis of concurrent surge and wave data at Tofino. The analysis concludes that the largest waves are not correlated with the largest storm surge events. This finding is supported by a very preliminary analysis for Squamish and (based on third-party information) by the more involved hindcasting analysis completed for the City of Vancouver. The question of wave-surge correlation should be a high priority for further investigation, and findings should be reflected in the revised FHALUMG.

- The Draft Amendment makes reference to "estimated wave effects associated with the Designated Storm". The term "Designated Storm" should be defined within the Draft Amendment. Until new studies become available, we expect that the revised FHALUMG will define the Designated Storm as the storm resulting in the most critical time series of wind speed and direction having a 200-year return period. If wind waves are not fully correlated with storm surge, then the addition of a 200-year return period design wave to the 200-year return period DFL could make the resulting Total Water Level much more conservative than the intended 200-year return period minimum target.

- The Draft Amendment's 200-year return period minimum target is expected to apply to the majority of BC's developed and potentially-developable coastal lands, where ground elevations are metres above mean sea level and coastal flood hazards are transient. It would be prudent to apply a more conservative DFL in areas where coastal flooding could occur more regularly and/or be of higher consequence (e.g., for areas where the ground level is below typical future high tides and/or the level of development is extensive). A well-known international example is the Netherlands, where large areas of the country lying below mean sea level are protected to a 10,000-year return period standard.

- Regardless of what minimum standard is ultimately reflected in the revised FHALUMG, local authorities should be explicitly encouraged to pursue higher levels of protection where justified by benefit-cost analysis or other forms of Quantitative Risk Assessment (QRA).

Update to SLR Guidance

The provincial SLR guidance of 1 m by Year 2100 / 2 m by Year 2200 is simple and transparent, and in general has been embraced by the engineering community. However, the Draft Amendment acknowledges that the SLR guidance should be reviewed in 2015.

Before the revised FHALUMG are officially released, it would be appropriate to review the SLR guidance and provide an update if required.

Acceptable Methodologies for Estimating FCL

The Draft Amendment outlines two alternative approaches for evaluating coastal FCLs. The only significant difference between the two approaches is the procedure for estimating the DFL. The "Combined Approach" estimates tide and surge independently and combines them additively, while the "Joint Probability Analysis" (JPA) approach examines statistical combinations of the two processes. Other methods for estimating the DFL include statistical frequency analysis of extreme water levels and "hindcasting" using a continuous-simulation wind wave model.

KWL has reviewed alternative methodologies for estimating coastal Flood Construction Levels (FCLs), most recently for the District of Squamish Integrated Flood Hazard Management Plan (IFHMP). Each of the approaches listed above is discussed below in the context of KWL's recent experience.

Combined Approach

In general, the "Combined Approach" outlined in the 2011 Ausenco Sandwell reports provides a rapid, straightforward, and conservative approach for estimating coastal FCLs. While the procedure is clear, we have questions about the assumptions applied to generate return periods for the DFL (tide / surge component). A review of these assumptions is provided in KWL's forthcoming Background Report for the Squamish IFHMP, previously shared with MFLNRO representatives sitting on the IFHMP Technical Working Group. We expect that the Combined Approach will remain a valuable tool for establishing an initial approximation to the coastal FCL. As the body of work on statistical analysis of coastal FCLs increases, it may be possible to refine the assumptions of the Combined Approach.

Joint Probability Analysis

JPA in the context of the Draft Amendment should refer to a comprehensive evaluation of the annual probability of equalling or exceeding a specified water level, determined by allowing tide and storm surge to fluctuate freely through their full range of expected values and with due regard to seasonality, timing, surge duration, and event succession.

As part of the Squamish IFHMP, KWL prepared a true JPA of tide and storm surge. KWL considered a range of storm surge magnitudes, seasonality and durations over a 19-year lunar tide cycle. No special software was required for this analysis, and all relevant data is available free-of-charge from Canadian Hydrographic Services (CHS). David Roche of KWL provided Inspector of Dikes Neil Peters with a complete methodology for KWL's process in an email dated October 3, 2014. KWL welcomes any feedback, comments, or suggestions regarding the process outlined therein.

The numerical differences between the Combined Approach and KWL's JPA for Squamish are summarized as follows (all elevations expressed in approximate geodetic datum):

Method	200-yr RP Event	4,000-yr RP Event
Combined Approach	2.82 m	3.17 m
Joint Probability Analysis	2.67 m	2.87 m
Note: Elevations shown above are converted from Chart Datum to approximate geodetic datum using an adjustment of 3.08 m for Squamish, provided to KWL by CHS in August 2014.		

The above table shows that the difference in DFL is relatively modest at the 200-year return period but increases as events become more extreme. KWL has no reason to expect that the results would be significantly different for other locations. KWL's JPA involves more engineering effort than the Combined Approach; as per the Draft Amendment, local authorities should be allowed to decide whether a potential reduction in FCL justifies the engineering costs of a JPA assessment.

JPA requires locally-representative data for both continuous tide predictions and historic storm surge events. After careful consideration, KWL's IFHMP storm surge analysis was based on data collected at the Point Atkinson CHS gauge. This is in contrast with Ausenco Sandwell's 2011 recommendation to use storm surge data from Tofino for all of Juan de Fuca Strait and Georgia Strait. The Draft Amendment is appropriately silent on the best source of data, leaving this decision to the Qualified Professional (QP).

Statistical Frequency Analysis of Recorded Extreme Water Levels

Intuitively, JPA results should be comparable to an extreme-value frequency analysis of a long and reliable series of observed water levels.

KWL did not undertake frequency analysis for the Squamish IFHMP; however, the District of Squamish provided KWL with a 2014 reference report by Tetra Tech EBA which estimates a 200-year return period DFL (tide + surge combination) of 2.68 m geodetic elevation. The JPA and statistical frequency analysis approaches provide identical results for Squamish.

Statistical frequency analysis is only viable where locally-representative, reliable observed water level data are available over a sufficiently long period of record. KWL believes that the decision as to what constitutes "locally-representative", "reliable" and "sufficiently long" may be left to the QP.

Hindcasting using a Continuous Simulation Wind Wave Model

KWL understands that the City of Vancouver has recently completed a comprehensive hindcasting exercise to define their coastal FCLs. In theory, a comprehensive hindcasting exercise would effectively replicate KWL's JPA in a modelling environment that can also incorporate wind and wave effects.

Although KWL has not had the opportunity to review the City's technical report, we believe that proper application of such an approach would have the potential to produce more robust estimates than can be obtained from either KWL's JPA or the Combined Approach. By incorporating wind waves and water level, the hindcasting approach explicitly estimates Total Water Level, thereby avoiding the potentially conservative combination of a 200-year return period DFL with a 200-year return period design wave.

We anticipate that a hindcasting analysis may not be practical for some jurisdictions given the higher engineering costs and the need for reliable long-term wind and water level data.

Summary of Approaches

In summary, we recommend that the FHALUMG make provision for three or four acceptable methodologies at increasing levels of effort and robustness:

Method	Effort / Data Requirements	Resulting FCLs
Combined Approach	Lowest	Highest
Joint Probability Analysis (also Statistical Frequency Analysis where observed data permit)	↓	↑
Hindcasting Analysis	Highest	Lowest

Additional Factors to Consider in FCL

Our review has identified a number of additional factors relevant for developing coastal FCLs in BC. These include local effects, wave effects and freeboard considerations, and secondary sources of flooding. Each of these factors is discussed separately below.

Local Effects

Uplift and subsidence processes are explicitly addressed in the Draft Amendment. However, local effects can also include wind setup, which is not included. The 2011 Ausenco Sandwell Sea Dike Guidelines note that local wind setup can occur in water depths less than 30 m and is not usually reflected in deep-water tide records. KWL recommends that the revised FHALUMG incorporate an appropriate allowance for local wind setup.

The Designated Storm used to estimate wave effects should also be the basis for estimating local wind setup.

Wave Effects and Freeboard Considerations

The perceived intent of the Draft Amendment is that wave effects will be evaluated as a product of the Designated Storm and the Year 2100 DFL, since seastate (and design wave height) can be sensitive to water depth. This will be obvious to most QPs, but MFLNRO should clarify this requirement in the revised FHALUMG.

Freeboard considerations in BC have historically been relatively simple, in part as a result of the traditional focus on river flood hazards. Freeboard for coastal situations is more complex; the natural variability of the seastate means that there is always a non-zero probability of waves exceeding design wave height. The question of freeboard, and more generally the specification of a coastal FCL, must consider the natural variability of the seastate during the Designated Storm.

KWL recommends that MFLNRO give further consideration to this issue and either specify a design wave condition (e.g., runup associated with the 2% exceedance wave at the location of interest) or functional objective(s) based on average rates of overtopping (e.g., no damage to property or the environment and no risk to public safety).

It is presently unclear how wave effects should be incorporated into the FCL for areas that are or will be protected by standard dikes. The Draft Amendment requires that buildings protected by standard dikes meet the FCL prescribed for the primary hazard adjacent to the dike. This is a well-known challenge for river floodplains: the "confined flow" FCL at the dike is unrealistic for dike breach or overtopping scenarios that would initiate conveyance through the protected floodplain.

An analogous but different challenge exists for sea dikes. Extrapolation of the still-water DFL is entirely appropriate for coastal margins, but a sea dike will usually experience greater wave effects than a sheltered or appropriately set-back building, with a correspondingly higher FCL. It may be physically impossible to experience the FCL from the adjacent dike at the location of interest. In addition, wave heights may vary along the length of a sea dike and the most appropriate location for determining a coastal FCL may not be clear.

Potentially acceptable alternative approaches to establishing a wave allowance within dike-protected areas are listed below, again reflecting differing levels of effort and robustness:

Method	Effort / Data Requirements	Resulting FCLs
Use expected wave effects at the adjacent dike alignment (as per the Draft Amendment)	Lowest	Highest
Estimate wave effects at the location of interest as if there were no primary dike	↓	↑
Estimate wave effects associated with a critical dike breach scenario	Highest	Lowest

If the revised FHALUMG do not provide guidance on appropriate approaches for estimating site-specific FCLs, local and provincial authorities should expect to see a variety of site-specific and/or project-specific assumptions.

Secondary Sources of Flooding (for Areas Protected by Coastal Dikes)

The question of appropriate freeboard is more complex for sea dikes where overtopping calculations come into play and the minimum freeboard could vary with overtopping rate. Ausenco Sandwell's 2011 Sea Dike Guidelines provide an illustrative calculation to demonstrate how overtopping can contribute to secondary flooding over the course of a six-hour storm. MFLNRO should consider an explicit reference to overtopping as a potential secondary source of flooding in Section 3.6.1.

Another special case meriting consideration is that of enclosed or "bathtub" areas where coastal flood protection works could retain water from an upstream river dike breach until it begins to spill out over the sea dikes. Such situations must be handled on a site-specific basis; the revised FHALUMG should require a site-specific assessment for potential enclosed or "bathtub" areas under Section 3.6.1.

Considerations for Coastal Setbacks

The Draft Amendment currently outlines building setback requirements separately for the Strait of Georgia and for areas outside the Strait of Georgia. Comments on these two areas are provided separately, as are KWL's comments on setbacks for coastal bluffs.

Strait of Georgia Area

Within the Strait of Georgia, the Draft Amendment defines the minimum setback as the greater of:

- 15 m from the estimated future Natural Boundary of the sea; or
- the location where the future FCL intersects the natural ground elevation contour.

Estimating the future Natural Boundary of the sea can be complex. We assume that the Draft Amendment reflects the concept of the Flood Construction Reference Plane (FCRP) as defined in Ausenco Sandwell's 2011 Guidelines for Management of Coastal Flood Hazard Land Use. Ausenco Sandwell defines the FCRP as the Designated Flood Level (still-water condition) plus a preliminary allowance equal to 50% of the estimated wave runup on the future shoreline. MFLNRO may wish to consider whether this approach provides a satisfactory estimate of the future Natural Boundary, and incorporate those conclusions into the revised FHALUMG.

The Draft Amendment's definition of setback (i.e., as the location where the future FCL intersects the natural land surface) implicitly supports the politically-difficult philosophies of "Avoid" and "Retreat" for coastal floodplain areas. Large areas of the low-lying BC coast will likely prove to be lower than the future FCL, particularly when applying the upper end of provincial SLR guidance. The revised FHALUMG should clearly state whether the specified setbacks are intended to support strategies of "Avoid" and "Retreat", which are otherwise absent from the Draft Amendment.

Finally, MFLNRO may wish to carefully consider the use and appropriate definition of "natural" within the phrase "natural ground elevation contour". At what point does a historic fill become the "natural" ground? We expect both developers and local authorities to raise questions about whether structural fill can be used to bring broad areas up to the FCL.

Areas Outside the Strait of Georgia

For areas outside the Strait of Georgia, the Draft Amendment outlines several setback requirements and generally requires that the most stringent requirement be adopted. Setback requirements for these areas include:

- setback determined from a site-specific tsunami hazard assessment (see tsunami discussion below);
- 30 m from the future Natural Boundary of the sea; or
- by implication, the location where the natural ground elevation contour meets the FCL that would be defined in the absence of a tsunami hazard.

The last requirement is defined "by implication", since the lead-in text to Section 3.5.6 of the Draft Amendment references the "standard" setbacks outlined in Section 3.5.5.1.

The Section 3.5.5.1 requirement for a 15 m setback from the future Natural Boundary of the sea is superceded by the Section 3.5.6 requirement for a 30 m setback from the future Natural Boundary. We are unclear on why these values are different, given that the Draft Amendment requires a separate assessment of tsunami hazards. We suggest that the revised FHALUMG harmonize these requirements.

Coastal Bluffs

The Draft Amendment specifies special setbacks for lots within the Strait of Georgia area that contain coastal bluffs steeper than 3H:1V. Stated requirements are as follows (sec. 3.5.5.4, p.3):

1. *If the future estimated Natural Boundary is located at least 15 m seaward of the toe of the bluff, then no action is required and the setback should conform with other guidelines that adequately address terrestrial cliff and slope stability hazards.*
2. *If the future estimated Natural Boundary is located 15m or less seaward of the toe of the bluff, then the setback from the future estimated Natural Boundary should be located at a horizontal distance of at least 3 times the height of the bluff, measured from 15 m landwards from the location of the future estimated Natural Boundary.*

We understand that the flood protection setback requirements above are intended to supplement, rather than replace, geotechnical setbacks related to terrestrial cliff and slope stability hazards. This consideration is more general than the proposed wording in sub-item (1) suggests, and should be promoted (i.e., to the lead-in to Section 3.5.5.4). MFLNRO may wish to consider a similar statement relating to environmental setbacks.

The two requirements set out in the Draft Amendment are reasonable at first glance, but when taken together they define a discontinuous setback requirement that could prove problematic. For example, a 10 m high bluff set back 15.1 m from the future Natural Boundary would be subject to the minimum 15 m setback. In contrast, a 5 m high bluff originating 14.9 m from the future Natural Boundary would be subject to a setback requirement of 30 m from the natural boundary.

We recommend that MFLNRO simplify and standardize the requirement for coastal bluff setback to 15 m plus three times the height of the bluff, measured from the Natural Boundary of the sea.

The Draft Amendment does not specify any special setback requirements for coastal bluffs located outside the Strait of Georgia. We are not clear on why a different standard would apply in different areas; prudence suggests that MFLNRO harmonize this requirement in the revised FHALUMG.

Areas Protected by Standard Dikes

The lead-in text for Section 3.6 of the Draft Amendment requires that residential, commercial, and institutional developments must comply with full floodproofing requirements for their respective categories. However, Section 3.6 also includes provision for "[r]elaxation of FCL requirements" in areas protected by standard dikes where a long-term flood protection strategy and a diking program have been approved by the Inspector of Dikes.

Corresponding relaxation of FCL-related setback requirements is implied, but it would be appropriate for MFLNRO to change the reference from "[r]elaxation of FCL requirements" to "[r]elaxation of both FCL and FCL-related setback requirements".

MFLNRO may also wish to refer to site-specific mitigation requirements recommended by a QP (e.g., as per the APEGBC 2012 guidelines, discussed below) in establishing the relaxed FCL.

Areas Where "Natural Boundary" Setbacks May Not Be Applicable

Careful examples of existing development can demonstrate that minimum setbacks from the Natural Boundary of the sea may not be necessary to mitigate flood hazards under very specific site conditions. In particular, minimum setbacks measured from the Natural Boundary of the sea may not be applicable for buildings located on, and structurally connected to, bedrock. MFLNRO may also wish to consider setback variations for special situations where a waterfront building can be heavily fortified and has the support of the local authority as well as environmental regulators.

All such cases should be subject to a site-specific analysis that specifies an appropriate FCL and is supported by the local authority and environmental regulators.

Considerations for Tsunamis

The Draft Amendment states that FCL requirements for tsunami hazard areas should be established on a site-specific basis. It would be very difficult to provide full protection against tsunami hazards using FCLs alone. A risk-based assessment that includes warning and evacuation procedures for rare events is entirely appropriate.

The Draft Amendment does not provide any guidance on acceptable risk or design event for a tsunami scenario. Definition of acceptable risk or a probabilistic minimum requirement (e.g., return period) for hazard assessment would provide QPs with a common starting point for performing site-specific studies. It could also support a distinction between existing and new development that is currently absent from the Draft Amendment.

Alternatively, MFLNRO may wish to work with EMBC to prepare a separate guidance document for comprehensive tsunami hazard mitigation planning, and reference that document in the revised FHALUMG.

The minimum standard cited in the Draft Amendment is the tsunami resulting from the Alaska earthquake of March 28, 1964. However, the Draft Amendment does not suggest where or how these minimum effects should be evaluated; observed effects were variable along the BC coast. This can be a particular challenge given the potential for a similar earthquake to occur at other locations around the Pacific Rim, including within the Cascadia Subduction Zone. Caution should be used in specifying the site-varying effects of the 1964 tsunami as a minimum target for flood hazard management.

The Draft Amendment also does not mention whether the site-specific study should consider the potential for:

- convergence and resonance processes, which amplified damage during the 1964 tsunami at Port Alberni; or
- local (e.g., landslide-induced) tsunami, which have previously produced runup of about 8 m in the aftermath of the 1975 landslide in Kitimat Inlet, and in tens of metres in Alaska.

Summary of Recommendations

The discussion above highlights a number of issues that MFLNRO may wish to consider when finalizing the revised FHALUMG. These recommendations represent the consensus opinion of the named flood hazard management professionals, and can be summarized as follows:

1. Work with APEGBC to harmonize FHALUMG revisions with a future update or addendum to APEGBC's 2012 document "Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC".
2. Define the minimum requirement for coastal flood hazard analysis in terms of Total Water Level, acknowledging that most approaches for estimating Total Water Level necessitate some simplifications.
3. Retain the 200-year return period event as the minimum requirement for coastal flood hazard assessments and mitigation planning.
4. Consider the need for a more conservative requirement in developed areas where coastal flooding could occur more regularly or be of higher consequence (e.g., where natural ground elevations are below future high tide, and/or there is extensive development).

5. Pursue further research into wind and wave correlation with storm surge along the BC coast as a high priority, preferably with results delivered before the FHALUMG are finalized.

6. Define the Designated Storm (for estimating wave effects) to achieve a realistic condition concurrent with the DFL. If no new research is available, define the Designated Storm as the storm resulting in the most critical time series of wind speed and direction having a 200-year return period but acknowledge that the resulting Total Water Level may have a higher return period.

7. Explicitly encourage local authorities to adopt a higher target for protection where justified by benefit-cost analysis or other forms of Quantitative Risk Assessment.

8. Review SLR guidance to confirm whether an update is required to support a 2015 revision of the FHALUMG.

9. Provide a definition for "Joint Probability Analysis" that balances technical accuracy against clarity for the public, based on KWL's suggestion herein or another appropriate source.

10. Define a suite of approaches of varying complexity that are acceptable for determining FCLs, and allow local authorities the freedom to select the approach that best meets their needs. Acceptable approaches could include the Combined Approach, JPA, and hindcasting.

11. Statistical frequency analysis of observed water levels could be considered an acceptable approach where the observed series of water level is sufficiently long and reliable.

12. Incorporate a requirement to consider local wind setup for all areas.

13. Define the Designated Storm as appropriate for determining wave effects and local wind setup, e.g., as the storm resulting in the most critical time series of wind speed and direction at a 200-year return period.

14. Clarify that wave effects should be determined as a product of the Designated Storm and the Year 2100 DFL.

15. Specify a design wave condition or functional objective(s) for the purposes of estimating wave effects (e.g., the 2% exceedance wave).

16. Allow for alternative approaches to establish an FCL wave allowance within dike-protected areas where the wave allowance at the adjacent dike is not realistic for the location of interest.

17. Update Section 3.6.1 to acknowledge overtopping and upstream dike breach as potential secondary sources of flooding.

18. Provide information on acceptable means of estimating the future Natural Boundary of the sea (e.g., reference to Ausenco Sandwell concept of Flood Construction Reference Plane) for the purposes of establishing building setbacks.

19. Strengthen the implicit connection between Draft Amendment setback requirements and the floodplain management strategies of "Avoid" and "Retreat", if such is the intent of the revised FHALUMG.

20. Review the concept of "natural ground elevation contour" with regard to historic fill and expected proposals for lot-scale or subdivision-scale structural fill in marginal areas.

21. Harmonize the minimum setback values within and outside the Strait of Georgia, recognizing that setbacks for tsunami hazards for the latter area must be assessed separately.

22. Relocate the existing reference to geotechnical setbacks in coastal bluff areas to make it clear that the revised FHALUMG is intended to supplement, rather than replace, applicable geotechnical setbacks.

23. Simplify and standardize the requirement for coastal bluff setback to eliminate the discontinuous requirement implicit in the Draft Amendment.

24. Harmonize coastal bluff setback for areas within and outside the Strait of Georgia.

25. In Section 3.6 of the Draft Amendment, clarify that the relaxation of FCL requirements also includes FCL-related setback requirements.

26. Consider providing additional guidance on how a relaxed requirement for FCLs and FCL-related setbacks might be specified (e.g., by a QP as per the APEGBC 2012 guidelines).

27. Consider allowing a variance on setbacks from the "natural boundary" where buildings can be constructed on exposed bedrock. Exceptions may also be considered for specialized structures that can be heavily fortified for site-specific waterfront locations.

28. Provide direction on "acceptable risk" or minimum hazard levels for site-specific tsunami studies in areas outside the Strait of Georgia.

29. Clarify the intent of reference to the 1964 tsunami, particularly if the intent is to incorporate anything beyond the site-varying local effects that were actually observed along the BC coast.

30. Consider providing examples of considerations that should be addressed in a site-specific tsunami study, including convergence, resonance and local tsunami hazards.

We trust that this response provides a clear synopsis of our position on the Draft Amendment and recommendations for finalization. We thank you again for your leadership on this important issue and for the opportunity to provide feedback to help shape the future of coastal flood hazard management in BC. Should you have any questions or wish to discuss any of the comments or recommendations herein, please contact the undersigned at your convenience.