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THE DEVIL IS IN THE DETAILS: ASSUMPTIONS AND REALITY COLLIDE IN URBAN DIKE BREACH MODELLING

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Abstract: Two-dimensional hydrodynamic modelling is a preferred tool for simulating complex outflow from dike breaches in urban areas. As always, engineers must ensure that results are based on an appropriate suite of assumptions and processes. Too much detail increases engineering costs while too little can lead to misleading model results and inefficient risk mitigation decisions. The costs of such decisions can exceed the modelling budget by orders of magnitude as risk management strategies are implemented. As part of the District of Squamish Integrated Flood Hazard Management Plan (IFHMP), a detailed dike breach model was developed for the Squamish River floodplain. The model considers the interdependence between architecture and preferential flow pathways as well as alternative representations of floodplain structures, compatibility of climate change and development assumptions, the iterative nature of floodproofing and flood risk, and the potential for breaches occurring anywhere along the developed floodplain's 20 km perimeter. To further complicate matters, Squamish's sea level rise planning area and river dike breach zone overlap within the downtown core. The IFHMP explores options for a sea dike and examines the effects of intentionally breaching the proposed sea dike to reduce floodplain inundation during a river dike breach. Model results highlight some significant changes from the (now decades-old) 1D modelling. Squamish faced difficult decisions about long-term floodplain land use and upgrades to the dike system. Detailed modelling supported the adoption of new structural, non-structural and policy measures to manage flood risk as part of a sustainable community plan.

1 INTRODUCTION

In 2014, the District of Squamish (District) retained a multidisciplinary consulting team led by Kerr Wood Leidal Associates Ltd. (KWL) to prepare an Integrated Flood Hazard Management Plan (IFHMP). The three-year project is summarized in a series of four reports that provide Squamish with an updated suite of tools for managing flood risk (KWL, 2017a, b, c; KWL and Arlington Group, forthcoming). The scope of work included two-dimensional (2D) hydraulic modelling of the Squamish River and Mamquam River floodplains under dike breach conditions. The 2D modelling described herein superseded steady-state 1D modelling completed as part of the District's 1994 Flood Hazard Management Plan (Klohn Leonoff, 1994).

The objectives of the 2D dike breach modelling were to better understand how the hazards of a dike breach would affect and interact with floodplain development, and to support a discussion of mitigation opportunities. A key modelling deliverable was the generation of new Flood Construction Levels (FCLs) appropriate for development and redevelopment within the dike-protected floodplain areas, as required by BC provincial guidelines (BC MWLAP, 2004). Other modelling deliverables included inundation depth maps, flood velocity maps, and physical hazard maps based on the United Kingdom's Hazard Rating concept (i.e., identifying the most critical combination of depth and velocity).

A total of eight dike breach scenarios spread across two floodplain areas provided a baseline indication of hazard and consequence using a simplified assessment procedure that focussed on a subset of potential hazards. Model scenarios were selected to reflect the conditions most likely to govern flood risk management decisions, considering flood magnitude, planning horizon, and breach location.

The District was particularly interested in moving beyond a simple hazard assessment toward a risk-based approach. Although available funding did not support a comprehensive Quantitative Risk Assessment (QRA), model results were used to generate economic consequence calculations using the HAZUS-MH platform. Social and economic consequences were assessed using new GIS algorithms developed as part of the IFHMP. The complete suite of consequence results can be incorporated into a comprehensive QRA framework as more modelling is completed under future projects. The model itself will be updated periodically to evaluate development applications that propose to vary existing zoning or land use.

The most important consideration for the model was to balance simplifying assumptions needed to meet scope and budget constraints against the need for detail in representing complex floodplain behaviours. Failure to achieve an appropriate representation could leave the District and its constituents exposed to unacceptable risks or facing millions of dollars in costs for excessive mitigation over the lifespan of the IFHMP. This paper describes the balance between simplicity and detail that was achieved for the IFHMP.

2 MODEL DOMAIN AND SETUP

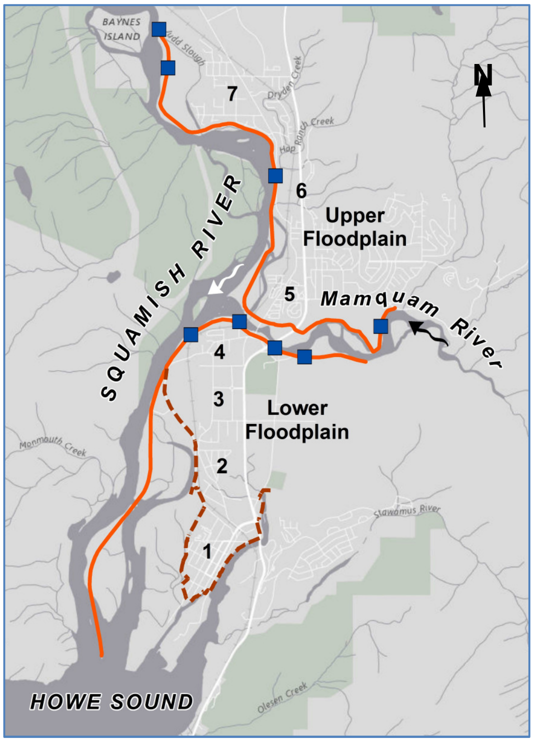
The Mamquam River divides the developed Squamish River floodplain into an "upper" (north) floodplain area and a "lower" (south) floodplain area (Figure 1). Each floodplain has an extensive urban footprint, and is protected by an independent dike system. This allows dike breaches on the upper and lower floodplains to be modelled separately.

Dikes at the downstream (south) end of the upper floodplain stop overland flow from returning to the river, and internal drainage works would be quickly overwhelmed or blocked during a dike breach event. Inflow from a dike breach is therefore trapped in the floodplain until it rises enough to overtop the confining dike. The result is extensive internal ponding (a "bathtub" effect) and water levels that exceed those in the adjacent river. A proposed sea dike around downtown Squamish will create a similar situation for the lower floodplain south of the Mamquam River, as shown in Figure 2 below.

The IFHMP Background Report (KWL, 2017a) updates pre-existing peak flow hydrology and 1D modelling of the Squamish River and Mamquam River. These updates become upstream boundary conditions for the 2D dike breach model. The report also describes a coastal flood analysis that provides downstream boundary conditions.

Modelling software had to be commercially available and able to integrate the pre-existing 1D river model with an unstructured, high-resolution 2D representation of the floodplain. DHI's MikeFlood software package was selected and run on a desktop PC with quad-core Intel i7 CPU at 2.8 GHz supported by 16 GB RAM. Two-dimensional calculations were executed using an NVIDIA Titan GPU. Simulation time for a single high-precision dike breach simulation varied from about one to several days, and would have been impractical without GPU parallelization.

Model topography was developed from a composite of high-resolution 2013 LiDAR, previous ground-level surveys of the river channels and dike crest, and near-shore coastal bathymetry data obtained from Canadian Hydrographic Services. The model incorporated cadastral, zoning, growth, roadway, and economic data drawn from the District's GIS system. Digitized roof polygons were also provided for existing buildings within the floodplain. High-level information concerning future land use for Squamish Nation Reserves within the floodplain was obtained directly from the Squamish Nation.



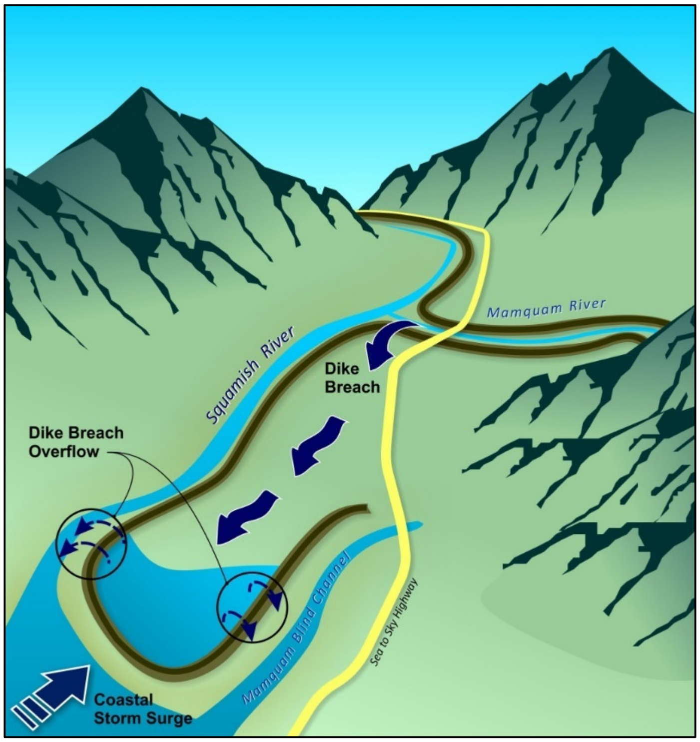


Figure 1 (Left): Squamish River floodplain showing river dikes (solid orange), future sea dike (dashed brown), and modelled breach locations (blue squares). Key at-risk areas include Downtown (1), Dentville (2), Industrial Park (3), North Yards (4), Garibaldi Estates (5), Eagle Run (6) and Brackendale (7)

Figure 2 (Right): Conceptual Illustration of Internal Ponding due to Upstream Dike Breach

Bed resistance uses a generalized representation of the floodplain's complex, spatially-varied roughness characteristics. Characteristic roughness values are assigned to polygons simulating city blocks (or large rural lots) and interstitial roads across the floodplain. Roughness values were weighted by governing land use. Since no calibration data are available, representative values for each land use were selected based on experience and engineering judgement. Initial water levels were set equal to the ground surface (for dry areas) and to a typical ponded elevation (for sloughs and ditches).

3 MESH DEVELOPMENT

The model's two-dimensional flexible mesh uses represents topography with a network of small triangular elements. Maximum default element areas of 500 m² provided the best balance between model efficiency and resolution. Size was reduced to 100 m² along the dike perimeter to improve flow exchange between 1D and 2D model components.

During a dike breach, flow concentration is expected along highways, local road networks, and other linear lower-resistance corridors. This is particularly important for densely developed areas where buildings, fences, and other obstructions limit conveyance through developed lots. Allowing mesh elements to span these linear corridors results in spatial averaging of elevation and roughness that in turn creates irregular and discontinuous conveyance capacity. This makes it extremely difficult to identify areas of elevated hazard within the model output. To provide more realistic floodplain hydraulics, linear features (dikes, railways, roads, etc.) were assigned a maximum element size of 10 - 20 m².

Buildings within a 2D model act as resistance elements to obstruct flow but also store water and thereby influence attenuation. For the IFHMP, consideration was given to ignoring buildings, excluding building footprints from the mesh, or modelling footprints with an elevated Manning's n value. Syme (2008) notes that blocking flow at the upstream building face while leaving the downstream side open can provide realistic results for both conveyance and storage; however, this more complex approach is not feasible when dealing with thousands of structures and multi-directional flow patterns.

After careful consideration, excluding building footprints from the mesh was selected as the most appropriate option for the Squamish IFHMP. This decision was based on the critical importance of conveyance and the availability of GIS roof polygons for existing floodplain structures. Implications of this assumption for floodplain storage and attenuation were checked and confirmed to be relatively limited. Building polygons were simplified and incorporated directly into the model's built-in mesh generator. Simplification was kept to the minimum required to achieve a stable mesh.

The final lower floodplain model contains about 184,000 individual mesh elements. The larger domain of the upper model has nearly 256,000 individual mesh elements. This is considered a relatively high resolution for 2D hydraulic modelling given the required scale, current tools and data limitations, and the processing capability of a single desktop computer. Testing clearly demonstrated the importance of the high-resolution mesh in simulating realistic floodplain behaviour (Figure 3).

Figure 3: Detailed representation of the floodplain (left) supports a more nuanced analysis of maximum Hazard Rating (depth x velocity, right), particularly where flow is concentrated along the road network

4 FUTURE CONDITIONS

Flood hazards are not constant in time, and may increase as a result of climate change. Guidance from provincial regulators requires that BC professionals consider 1 m of Sea Level Rise (SLR) by Year 2100 and 2 m by Year 2200 (BC MFLNRO, forthcoming), as well as a minimum +10% adjustment to peak discharges (APEGBC, 2012).

The consequences of a given flood hazard can also increase as a community expands or intensifies its development of floodplain areas. Changes can affect both new elements at risk (i.e., new infrastructure and populations) and existing elements (e.g. as new development reduces conveyance and raises upstream water levels). Failure to consider and plan for future conditions can leave today's developments exposed to unacceptable risk at the end of their service life.

As a rapidly-growing community in a high-hazard area, Squamish faces expected future changes in both hazard and consequence. The IFHMP dike breach model was adapted to explore potential flood risks under assumed Year 2100 conditions. Results may be sensitive to the resulting assumptions; however, the goal is to establish reasonable (rather than accurate) future conditions and considerable uncertainty can be tolerated. Sensitivity analysis would be appropriate but was beyond the project scope.

4.1 Year 2100 Flood Hazards

In the absence of a historical trend, river hydrographs were scaled up by 10% (APEGBC, 2012), and a constant 1 m was added to the coastal tide series to represent SLR (BC MFLNRO, forthcoming). Coastal storm surge, wind field and tide harmonics were assumed to maintain stationarity. Year 2100 wave conditions were assessed for the IFHMP but not incorporated into the dike breach model.

4.2 Year 2100 Floodplain Assumptions

Key Year 2100 floodplain modifications include floodproofing, allowances for infill development, and floodways. Floodproofing and infill development assumptions are based on District zoning data and high-level land use information provided by the Squamish Nation. The three types of modification are discussed individually below.

4.2.1 Floodproofing

There is an intuitive feedback relationship between future water levels and future floodproofing assumptions. The assessment process is typically iterative, since it is difficult to estimate with precision how the model results will respond to changes to the floodplain surface. Multiple simulations are usually completed to explore mitigation options and achieve an optimum balance between inflow, outflow, floodproofing, floodplain storage (attenuation), and conveyance.

Since an iterative approach to establishing future flood levels was beyond the project scope, FCLs from the 1994 Flood Hazard Management Plan (Klohn Leonoff, 1994) were used to approximate an initial suite of Year 2100 floodproofing targets. The implicit assumption is one of convergence in a single iteration (i.e., updating floodproofing assumptions would not have a significant effect on results). This approach results in considerable uncertainty where IFHMP FCL recommendations differ from the modelled conditions, but was the best approach possible given project funding and schedule constraints.

A multidisciplinary team of planners and engineers developed a suite of zoning-specific floodproofing allowances. The allowances target the 1994 FHMP FCLs but also recognize expected land use constraints. For example, large rural lots were not raised in the model, since the footprint of floodproofing fill relative to lot size would be small and unlikely have a significant effect on conveyance.

Floodproofing assumptions were applied in GIS based on the most representative zoning class for each city block. A buffer was retained at the outer perimeter of each block to allow the mesh generator to smoothly interpolate between Year 2100 fill assumptions and surrounding 2013 topography.

4.2.2 Infill Development

Infill development will increase the footprint of buildings on both occupied and vacant lots within each city block. These changes will reduce the effective conveyance of the floodplain. It is impossible to accurately predict how much and where infill development will occur. In accordance with District development objectives and to provide a conservative representation, each city block is assumed to infill to the maximum allowable footprint for its corresponding land use.

The percentage of each city block occupied by existing building footprint (if any) was determined and compared to the maximum allowed under the bylaw. Existing buildings are represented explicitly in the mesh. Potential increases in building footprint were represented by pro-rating each city block's roughness value assuming that the additional building footprint has a Manning's n value of 0.4 (Syme, 2008). The nature of infill development means that it is likely to be adequately served by existing roads, so no changes were required for the road network.

4.2.3 Floodways

In the IFHMP context, a floodway is a dedicated or *ad hoc* corridor that provides a continuous and unobstructed flow path during a dike breach scenario. Properly-planned floodways with sufficient capacity can help mitigate rate of rise and maximum water level in upstream areas, although they may create elevated hazards (due to higher velocities) along the floodway itself. Floodways also play an essential role in situations where gravity drainage works remain functional, or an intentional outlet dike breach could relieve an internal ponding condition.

The effectiveness of a floodway can only be confirmed through hydraulic modelling. The IFHMP incorporates floodways by maintaining present-day ground elevations along selected corridors where floodproofing fill would otherwise be applied.

5 MODEL SCENARIOS

Several factors must be considered when defining an appropriate portfolio of scenarios for dike breach modelling: floodplain area affected (e.g., upper or lower floodplain for the IFHMP), breach location and geometry, magnitude of concurrent river flood, magnitude of concurrent coastal flood, time horizon for modelling, and treatment of downstream dikes. Each of these factors is discussed individually below.

5.1 Concurrent Flood Conditions

A dike breach model is driven by a concurrent flood condition. Most often, the concurrent flood is assumed capable of overtopping, eroding, undermining, destabilizing or otherwise initiating a dike failure. The probability of hydraulically-induced failure is usually considered low (but not necessarily zero) for floods at or below the dike's design condition, and approaches unity when an earthfill dike is overtopped. The probability of a dike breach failure is therefore the product of the probability of the concurrent flood and the conditional probability of a dike breaching during that flood.

When an analysis is limited to a subset of potential hazard scenarios, flood scenarios must be carefully selected to provide a context-appropriate characterization of the risk. Because IFHMP model results would be used to generate FCLs, the study prioritized 1 in 200 Annual Exceedance Probability (AEP) design conditions for the concurrent river flood. Experience with seepage, piping, and compromised freeboard during past flood events suggests that the existing dikes have a non-zero probability of failure at similar discharges. Future work is expected to explore dike breach consequences under more extreme flood conditions.

Coastal flooding was assessed separately at the 1 in 200 AEP level; however, river and coastal floods at Squamish are not strongly correlated. Review of historical streamflow and metocean records suggests that the 1 in 10 AEP coastal flood at Howe Sound is an appropriate concurrent boundary condition for 1 in 200 AEP river flood simulations.

5.2 Breach Location

Early modelling showed that dike breaches were required at eight locations (shown in Figure 1) to adequately characterize the floodplain response. Each breach was positioned where experience suggests there could be an elevated risk of dike failure (landside sloughs, impinging flow, penetrations, etc.). Quantitative characterization of failure probabilities (e.g., using reliability functions in a Monte Carlo analysis) can be useful but is effort-intensive and beyond the scope of the IFHMP.

Breaches on the upper floodplain are hydraulically straightforward and strategically located to identify and characterize the floodplain's governing hydraulic behaviours and flow directions. Multiple breaches were required on the lower floodplain to capture preferential north-south flow along corridors defined by linear infrastructure (e.g., Highway 99, CN Rail mainline).

Each of the eight scenarios involves a single dike breach occurring at a unique location. Multiple dike breaches are possible, particularly as water levels approach widespread overtopping conditions; however, multiple breaches would tend to govern rate of initial rise more than ultimate water level due to the widespread internal ponding that occurs on the diked Squamish River floodplain. A detailed assessment of multiple-breach scenarios was beyond the scope of the IFHMP.

5.3 Breach Mechanics and Geometry

Dike breaches are relatively uncommon and their mechanics can depend significantly on situational factors such as breach mechanism, dike fill materials, construction standards, and local hydraulics. Lacking resources for quantitative characterization, the IFHMP relied on dike breach information provided in the Fraser Basin Council's 2004 floodplain mapping guidelines (WMC, 2004). Maximum dike breach widths of 200 m and 100 m are assumed for the Squamish River and Mamquam River, respectively. Breach growth is based on a historical relationship for sand dikes.

The model is expected to be relatively insensitive to the initial incision (assumed to progress from dike crest to floodplain in 0.25 h) and side slopes (assumed 1H:1V side slopes). The initiation mechanism for each breach is not specified and the breach mechanics are considered representative of a range of failure processes. All failures commence on the rising limb of the river hydrograph so that the breach is already well-developed when hydrograph peaks.

5.4 Time Horizon

Ideally, the IFHMP would evaluate both existing and future conditions. However, all eight available model scenarios were required to provide an adequate description of floodplain response for a single river flood. The need to craft stable long-term policy meant that the IFHMP had to prioritize future conditions. The focus on Year 2100 conditions means that IFHMP model results may not provide an accurate picture of existing or short-term risks under current development and mitigation conditions.

5.5 Outlet Dike Breaches

The District's emergency plan would be activated in response to any major river flood that could result in a dike breach. Advance planning can make provision for intentionally breaching downstream dikes to mitigate internal ponding and avoid a "bathtub" effect. High downstream river levels outside the Squamish River and Mamquam River dikes would limit the effectiveness of this approach for the upper floodplain, but the weaker correlation between coastal and river flood conditions make intentional breaches a more promising option for the future sea dike.

Outlet dike breaches have the predictable effect of reducing inundation depths but increasing velocity. Supplemental modelling was completed to assess the effect of adding intentional sea dike breaches into a river dike breach scenario (KWL, 2015). Increases in velocity and Hazard Rating were relatively modest and more than offset by significant decreases in maximum water level.

6 POST PROCESSING AND RESULTS

Post-processing algorithms played a key role in producing IFHMP technical deliverables. Specific post-processing tasks included compilation of model results, calculations to account for potential dike breaches at other locations, flood hazard map production, and consequence assessment. Each of these topics is discussed below.

6.1 Compilation of Model Results

Results from each of KWL's eight scenarios represent one possible flood scenario resulting from a dike breach at a specific location. Flood risk management policy must consider all possible outcomes. To be useful in a planning context, model results must be generalized and spatially comprehensive. The eight IFHMP dike breach scenarios were chosen and modelled specifically to support this process.

Post-processing combined scenario results into envelope surfaces of water level, flow velocity, and Hazard Rating by extracting the highest value for each mesh element. Results were then interpolated from point shapefiles (based on mesh element locations) to a continuous raster using standard GIS tools.

The resulting envelope surfaces provide an acceptable representation of generalized floodplain behaviour that is independent of dike breach location.

6.2 Breach Zone Calculations

The generalized results discussed above may not be the governing hazard in areas close to the dike where a local breach could generate higher velocities and inundation depths. Different agencies have different names for this area of local effect; the IFHMP refers to this area as the “dike breach zone”.

Because a breach could theoretically occur at any location along the dike, local effects within the dike breach zone must be approximated and incorporated into the final composite results. Key breach characteristics include water depth in breach, Hazard Rating in breach, and breach zone width. The IFHMP relates these hydraulic characteristics to maximum head, defined as the difference between a representative floodplain elevation and the corresponding maximum water surface elevation for the 1 in 200 AEP flood without dike breaches.

Maximum head can be calculated at any point along the dike profile and used to extrapolate potential breach characteristics. The IFHMP calculated potential breach water depth, Hazard Rating, and breach zone width at 10 m intervals along the ±20 km length of river dike. A spatially-distributed estimate of local effects was obtained by interpolating between breach characteristics at the dike and generalized floodplain results at the breach zone limit. Figure 4 shows an example of the locally-elevated results for Hazard Rating along the dike. Although there is considerable uncertainty in the breach zone results, the result is far more useful for mitigation and response planning than results based exclusively on a small number of assumed breach locations.

6.3 Final Map Production

Final water surface elevation, water velocity and HR rasters were produced by merging the dike breach zone results and coastal flood conditions with the envelope surface of 2D model results. Inundation maps were created by subtracting the 1 m resolution topographic raster from the final water surface elevation (Figures 5 and 6). Areas potentially subject to other hazards (debris flow, avulsion, overland flow, etc.) are indicated on the final IFHMP maps to highlight the need for further assessment. Internal drainage hazards can be incorporated once the District completes its planned Integrated Stormwater Management studies.

Considerable discussion was devoted to the concept of appropriate freeboard for floodplain FCLs. Freeboard (typically 0.6 m) is a required part of conventional FCL calculations in British Columbia, but there is no accepted standard for dike-protected areas. Due to the conservative suite of modelling assumptions, the comprehensive nature of the modelling, and the challenges associated with implementing future-oriented FCLs, no additional allowance for freeboard was applied within the diked Squamish River / Mamquam River floodplain.

The final flood hazard maps are composite envelope results that encompass the potential for a single breach occurring at any location along the Squamish River and Mamquam River dikes. This is the tool required for floodplain-level mitigation planning, which must consider and prioritize the hazards and consequences of multiple dike breaches. Weighting the hazard and consequence results by probability (i.e., as part of a risk assessment) would be beneficial but is beyond the scope of the IFHMP.

6.4 Consequence Assessment

The final hazard maps (flood level, depth, velocity and HR) served as inputs for a GIS-based consequence assessment. The inundation extents shown in Figures 5 and 6 were the basis for a $447 million lower-bound estimate of economic damages. Results also indicate that a dike breach could damage or destroy as many as 1,400 buildings and generate nearly 40,000 tonnes of debris. Over 50% of the population of Squamish could be displaced.

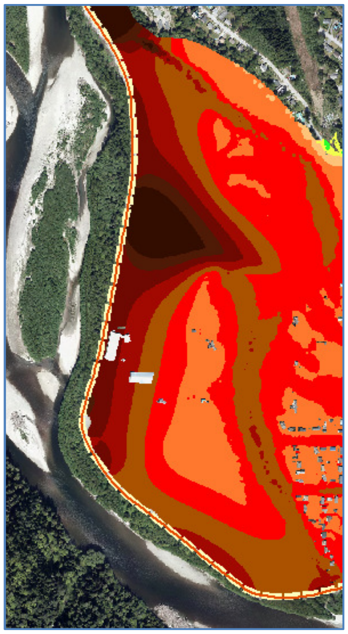
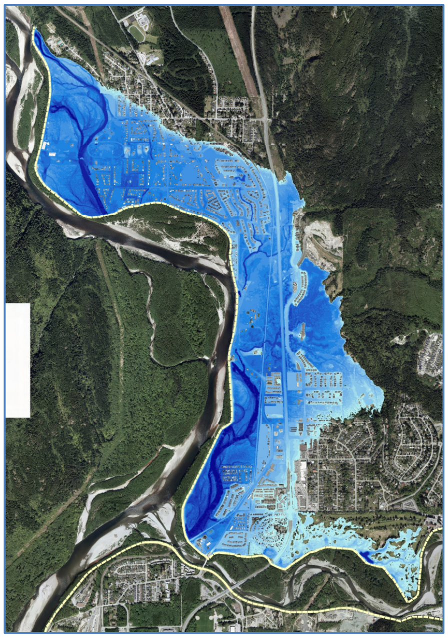
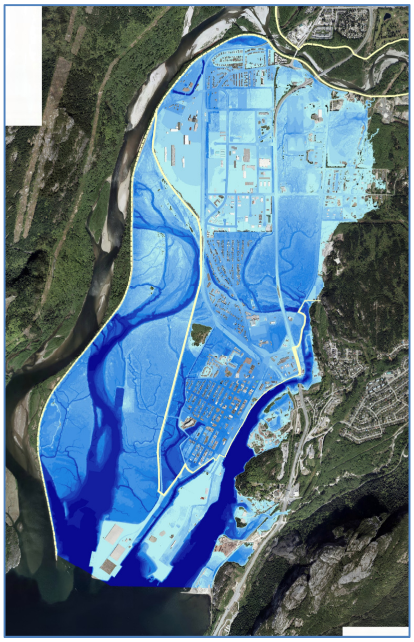




Figure 4 (Left): Map excerpt showing elevated Hazard Rating for dike breach zone along the land side of the river dike. Darker colours represent higher hazards

Figure 5 (Centre): Map excerpt showing dike breach inundation extents for the upper floodplain

Figure 6 (Right): Map excerpt showing dike breach inundation extents for the lower floodplain

Social consequences were assessed using a new GIS-based approach developed as part of the IFHMP. The process considers vulnerability, hazard intensity, and duration to assess displacement of residents, disruption of employment, and interruption of important community services. Maximum intensities for social consequence are governed by inundation of critical community facilities such as schools, wastewater treatment infrastructure and fire halls. The approach was also adapted to map environmental consequences at sensitive habitat areas and storage sites for potentially dangerous materials.

7 PROJECT OUTCOMES

The dike breach modelling and parallel assessments of other flood hazards formed the basis for a detailed flood risk mitigation strategy that includes over 100 specific management tools. The strategy incorporates elements of protection (diking), accommodation (floodproofing, appropriate land use, and designation of floodways), avoiding new risks, managed retreat of key infrastructure, and selectively accepting risk where it brings significant benefits for the community. Tools are grouped into seven categories: land use planning, development and building controls, structural flood protection, watershed and river management, public education, emergency planning, and flood insurance. Some of the most important aspects of the strategy include adopting a higher standard for high-consequence dike protection works, limiting densification in the highest-hazard parts of the floodplain, and directing growth to lower-risk areas of the community. Key deliverables included a prioritized list of structural flood protection upgrades, significant revisions to Official Community Plan hazard policies, the District's first Floodplain Bylaw, and new Development Permit Area guidelines for flood hazard lands.

A careful balance of simplifying assumptions and dike breach model complexity allowed the IFHMP to support both general and detailed outcomes. The importance of simplifying assumptions is clear from the complex combinations of hazard and consequence that could be usefully considered in risk mitigation discussions. At the same time, model complexity was essential for producing realistic results. The chosen level of complexity resulted in both direct and indirect benefits for the study; for example, the identification of severe hazard conditions on planned evacuation routes, the potential benefits of intentionally breaching a downstream dike, development of new algorithms to simulate local effects in the dike breach zone, and establishment of long-term FCLs that will not become “moving targets”. In addition, future work can leverage the detailed model to evaluate specific redevelopment proposals or produce a Quantitative Risk Assessment.

Not all dike breach assessments will require the Squamish IFHMP’s level of detail. The appropriate level of complexity will depend on project-specific factors: technical flood hazard, available data, project constraints and desired outcomes. Some issues – such as the consideration of multiple breach locations and the local breach zone – must be addressed to produce accurate results, while others – such as the incorporation of future development assumptions – may need to balance desired outcomes with more practical considerations. It is hoped that detailed studies like the IFHMP can help decision-makers reach effective decisions about costs, benefits and the most appropriate level of detail for their specific situation.

ACKNOWLEDGEMENTS

This work would not have been possible without the dedicated assistance of District of Squamish planning and engineering staff and the support of Mayor and Council. Technical advancements described herein are the result of a multidisciplinary effort that included engineers from KWL, SNC-Lavalin Inc., and Thurber Engineering Ltd., planners from Arlington Group Planning + Architecture, and environmental scientists from Cascade Environmental Resource Group. Graham Farstad of Arlington Group provided specific support for assumptions about future infill development. Outcomes were shaped in part by input from the District’s flood management partner Skwxwú7mesh Úxwumixw (Squamish Nation), a stakeholders’ Technical Working Group, and the Squamish community.

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