Spatial Representation of Wave Run-up in Regional Shoreline Floodplain Mapping

Vanessa McMaster[1], Edwin Wang[1] and Dale Muir[1]
Northwest Hydraulic Consultants, North Vancouver, BC, V7M 3G3, Canada [1]
E-mail: vmcmaster@nhcwater.com, ewang@nhcwater.com,
dmuir@nhcwater.com

ABSTRACT

Flood elevation and extent along coastal and lake shorelines reflect the combined influence of quasi-static water level and wave run-up. Along shoreline margins where waves break and run up the foreshore, development pressures are often greatest, and wave run-up can contribute substantially to flood elevation. Despite this influence, wave run-up is frequently omitted or coarsely approximated in flood mapping, particularly flood mapping at regional scale. This paper examines how wave run-up can be explicitly represented in floodplain mapping at a regional scale, where phase-solving wave modelling is not practical. An applied approach is presented that uses empirical run-up relationships evaluated along densely spaced shoreline transects, allowing spatial variability in wave exposure, nearshore depth, and foreshore characteristics to be represented. The approach is demonstrated through its application to floodplain mapping for Shuswap Lake and associated lakes in southern British Columbia, Canada, with a focus on supporting land use planning.

KEYWORDS: Floodplain mapping, wave run-up, land use planning, shoreline flooding

1 INTRODUCTION

Flood elevation and extent along a shoreline are governed by the combined effects of water level and wave run-up. Shorelines are often preferred locations for development, resulting in infrastructure and communities being located within areas subject to wave-affected flooding. Understanding and representing these combined processes is therefore an important component of floodplain mapping used to inform land use planning.

In many floodplain mapping studies, wave run-up is either omitted or represented indirectly through generalized freeboard allowances. While this approach may be expedient at a regional scale, it can obscure spatial variability in flood elevation along shorelines with differing wave exposure and foreshore characteristics such as slope and surface roughness. As a result, locations subject to elevated wave effects may not be clearly distinguished from more sheltered areas.

This paper addresses how wave run-up can be represented explicitly in regional floodplain mapping, where phase-resolving wave modelling is not practical due to computational and spatial-scale constraints. The objective is to present an applied approach that balances physical representation of wave processes with the constraints of large-area floodplain mapping and produces outputs suitable for supporting land use planning along shorelines and within lakeside communities. This paper focuses on wave run-up and does not describe methods to determine the (quasi-static) design still water level used for floodplain mapping within a lake or coastal environment.

1.1 Background and Motivation

Floodplain mapping in coastal and lake shoreline environments requires consideration of multiple interacting drivers, including water levels, wind forcing, wave generation, and foreshore characteristics.

In contrast to riverine settings, waves can elevate flood levels above design still water conditions through wave run-up, extending flood hazards landward along exposed shorelines.

In many regional floodplain mapping programs, wave effects are either omitted or addressed indirectly through generalized freeboard allowances. While expedient, this approach can mask spatial variability in wave exposure and foreshore conditions along shorelines, particularly where shoreline orientation, fetch, and nearshore geometry vary over short distances. As a result, areas subject to elevated wave influence may not be clearly distinguished from more sheltered locations, limiting the usefulness of floodplain maps for shoreline land use planning.

Wave effects in floodplain mapping are commonly represented through wave run-up, typically quantified using the 2% exceedance level ($R_{2\%}$). Run-up can be estimated using either phase-resolving wave models or empirical formulations. Although phase-resolving models can provide detailed estimates of run-up for specific sites, their data and computational requirements generally limit their application to small spatial extents, making them impractical for regional floodplain mapping. As a result, empirical formulations are commonly used at regional scales. These formulations relate run-up to incident wave conditions and simplified representations of foreshore slope and surface roughness. By definition, they estimate run-up elevations and do not resolve overtopping, ponding, or inland flow processes; requiring additional interpretation when applied for flood extent delineation.

In British Columbia, areas where wave action influences shoreline flooding are commonly referred to as the wave effect zone, reflecting recognition that waves can extend flooding beyond still water levels. However, despite this recognition, floodplain mapping guidance has not prescribed specific methodologies for explicitly representing wave run-up within this zone. Where wave effects are incorporated, they are typically represented in a coarse manner, using single run-up or freeboard values applied to representative shoreline segments based on generalized wave exposure and foreshore characteristics, rather than through spatially explicit mapping.

In other jurisdictions, such as the United States and Denmark, wave-related processes are considered within coastal flood risk and hazard frameworks. In the United States, wave effects are incorporated within FEMA's coastal flood studies primarily to support regulatory classification and insurance-related risk management, typically through transect-based analyses and zone delineation rather than spatially continuous mapping of wave run-up along shorelines. In Denmark, national and regional flood mapping efforts have focused largely on storm surge and inundation risk under the EU Floods Directive, with wave effects more commonly addressed through coastal protection design and site-specific engineering studies. These approaches serve different objectives and are generally oriented toward open-coast or defended shoreline settings and are therefore not readily transferable to regional floodplain mapping for large lakes or mixed shoreline environments, such as required in British Columbia.

While empirical wave run-up methods suitable for regional analysis are well established, there remains limited guidance on how to apply them in a spatially explicit manner to delineate wave-affected flood extents along long, heterogeneous shorelines for land-use planning. The approach described in this paper addresses this gap at a regional, planning scale.

1.2 Study Area

The approach described in this paper was applied as part of a regional floodplain mapping program for the Shuswap Region in southern interior British Columbia, Canada. The region comprises a system of interconnected lakes and rivers situated within mountainous terrain and includes Adams Lake, Mabel Lake, Mara Lake, Little Shuswap Lake, and Shuswap Lake. The lakes are characterized by long, irregular shorelines with variable orientation and wave exposure, collectively extending over approximately 500 km of shoreline.

Floodplain mapping for the region incorporated explicit estimation and mapping of wave run-up along lake shorelines to support delineation of shoreline flood hazards relevant to land use planning and development in lakeside communities. The Shuswap Region and the lakes included in the floodplain mapping are shown in Figure 1, with lake extents shown in yellow and shoreline areas mapped as part of this study shown in green.

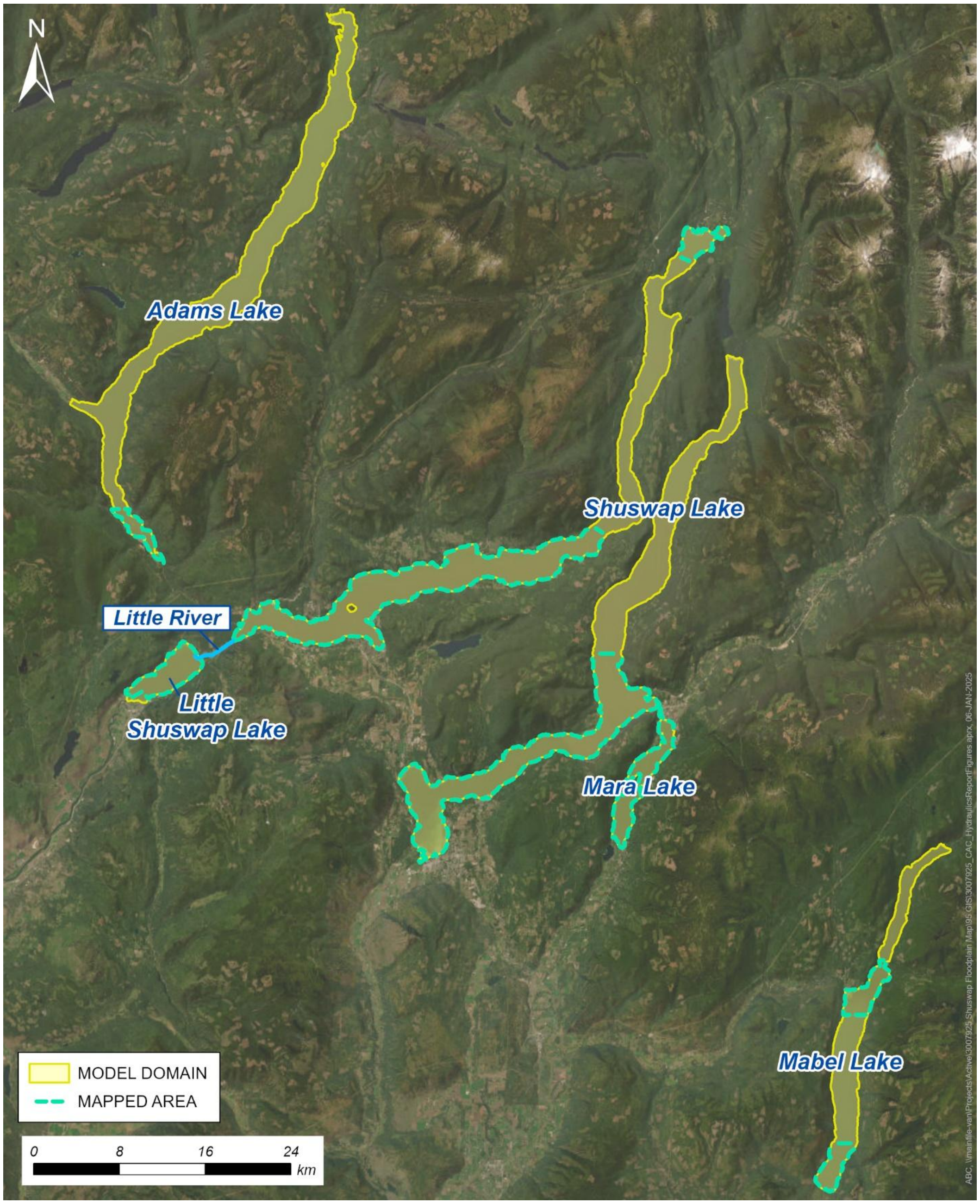

Figure 1: Shuswap Region lakes included in floodplain mapping

2 METHODS

This section describes the sequence of analyses used to estimate and spatially represent wave run-up for regional floodplain mapping. The overall approach consisted of:

(1) determination of design wind conditions and nearshore wave modelling to resolve spatial variability in wave exposure,

(2) generation of shoreline transects at defined spacing
(3) extraction of wave conditions and foreshore characteristics along each transect, and
(4) estimation and spatial mapping of wave run-up using empirical formulations.

2.1 Wind and Wave Analysis

A wind analysis was conducted to define design wind conditions for the study area. These conditions were used as input to a nearshore wave model to simulate the spatial distribution of wave height, period, and direction across the lakes under design water level conditions, accounting for variability in wave generation and propagation associated with lake geometry, fetch, and shoreline orientation.

Because shoreline exposure varies substantially with orientation and fetch, multiple nearshore wave model simulations were undertaken to represent different wind and wave scenarios relevant to the study area. The resulting wave fields provided spatially varying wave conditions along the lake shorelines. These wave conditions formed the basis for subsequent run-up calculations, with the maximum run-up response across applicable wave scenarios retained for floodplain mapping purposes.

2.2 Shoreline Transect Generation

Shoreline transects were generated at regular spaced intervals along the lake shorelines to provide consistent spatial coverage. Transect spacing was selected to balance representation of alongshore variability with practical limits on data processing and analysis effort, with additional transects introduced in locations where shoreline geometry, wave exposure, or development density changed over short distances.

Coastal and lake shorelines exhibit substantial variability in both the alongshore and cross-shore directions, with changes in slope, materials, orientation, and fetch occurring over relatively short distances. Because empirical run-up calculations are inherently local in application, closely spaced transects were used to reduce reliance on interpolation and to better represent localized variations in shoreline conditions. Transects were oriented approximately perpendicular to the local shoreline to represent cross-shore wave transformation and run-up processes.

Shoreline transects were generated at 250 m intervals along lake shorelines across the Shuswap Region, resulting in more than 2,000 transects in total. An example of transect distribution along the Shuswap Arm region of Shuswap Lake is illustrated in **Error! Reference source not found.**.

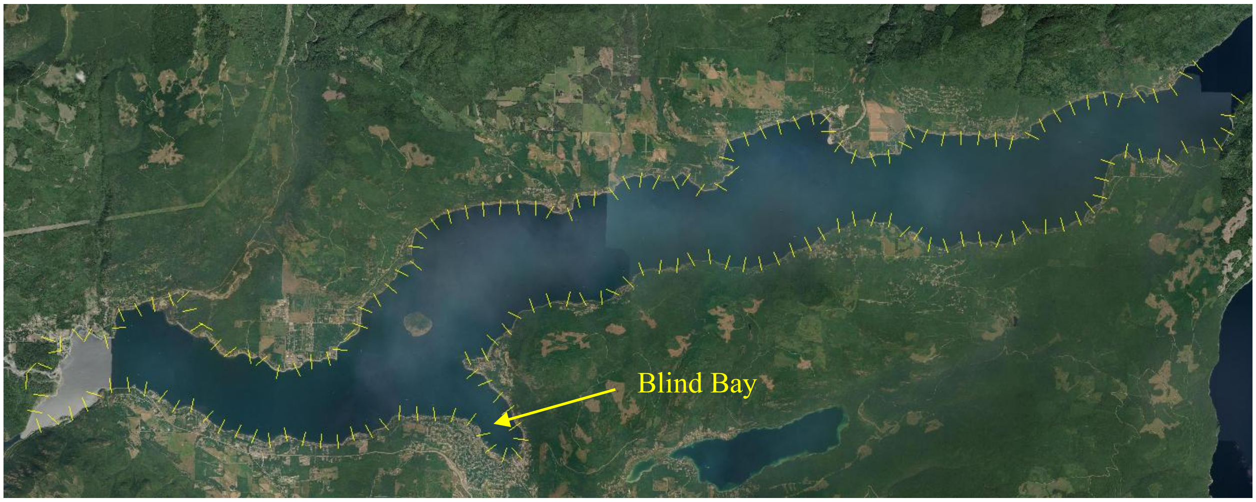

Figure 2: Transects to calculate wave run-up along Shuswap Lake

2.3 Extraction of Foreshore Characteristics and Wave Conditions

For each transect, wave conditions were extracted from the nearshore wave model outputs at the shoreline. Topographic and bathymetric data from a lidar-derived digital elevation model were used to extract shoreline profiles along each transect.

To obtain wave conditions representative of the toe of the shoreline, additional wave transformation was applied within the post-processing workflow. Shoaling and refraction were accounted for using transect-specific shoreline geometry and nearshore bathymetry, translating incident wave conditions from the nearshore model to the toe of shoreline, consistent with the input requirements of the empirical wave run-up formulations.

Foreshore slope was determined algorithmically from the extracted profiles relative to the design still water level, rather than through manual interpretation. This approach reduced subjectivity in slope selection and ensured a consistent and repeatable definition of foreshore slope across all transects. The same procedure can be applied directly to alternative water level scenarios, including design water levels under future conditions (e.g., climate change and subsidence), without requiring re-evaluation of individual shoreline profiles.

Foreshore surface roughness was characterized based on available spatial data, site observations, and interpretation of shoreline materials, consistent with the assumptions required by the selected empirical run-up formulations. Extraction of wave conditions, application of wave transformation, and determination of foreshore characteristics were implemented through a scripted workflow, ensuring consistent and repeatable application across all transects and wave scenarios.

2.4 Wave Run-up Estimation and Mapping

Wave run-up estimates were calculated at each transect using empirical formulations appropriate for the local foreshore characteristics. Empirical equations defined in EurOtop (2018) and the Stockdon (2006) equation for natural beach (slope < 10H:1V) were applied using inputs including significant wave height, wave period, wave direction, nearshore water depth, and foreshore characteristics such as slope and surface roughness. The resulting output at each transect was the 2% exceedance run-up level ($R_{2\%}$). For floodplain mapping, calculated wave run-up elevations were combined with the design still water level, wind setup, and adopted freeboard (applied in British Columbia along the shoreline to account for uncertainty) to define a flood construction level (FCL) along the shoreline.

Empirical wave run-up equations assume an idealized, continuous foreshore slope extending landward from the shoreline. Where this assumption is reasonably met, such as along uniform – steadily rising slopes, the calculated run-up elevation is typically reached within a short distance landward of the design still water level. However, shorelines that include low-gradient benches, berms, or engineered features, such as dikes or transportation embankments, may violate this assumption, resulting in calculated run-up elevations being projected unrealistically far inland if applied strictly based on elevation alone. In these settings, the empirical equations do not resolve overtopping, ponding, or inland flow processes. This limitation is illustrated conceptually in Figure 3, which contrasts wave run-up on a continuous sloping foreshore with conditions where a low-gradient bench or dike causes the infinite-slope assumption to break down.

Calculated FCL elevations were projected landward to the corresponding terrain elevation on a lidar-derived digital elevation model to delineate flood extent. To limit unrealistically large inland extends where the infinite-slope assumption is not met, the landward projection of wave influence was constrained to a maximum horizontal distance of 30 m from the intersection of the design still water level and the foreshore. This distance represents a planning-scale wave effects zone, consistent with emerging provincial floodplain mapping practice, and is intended to bound the zone of direct wave influence rather than to represent overtopping behaviour or inland flood hydraulics.

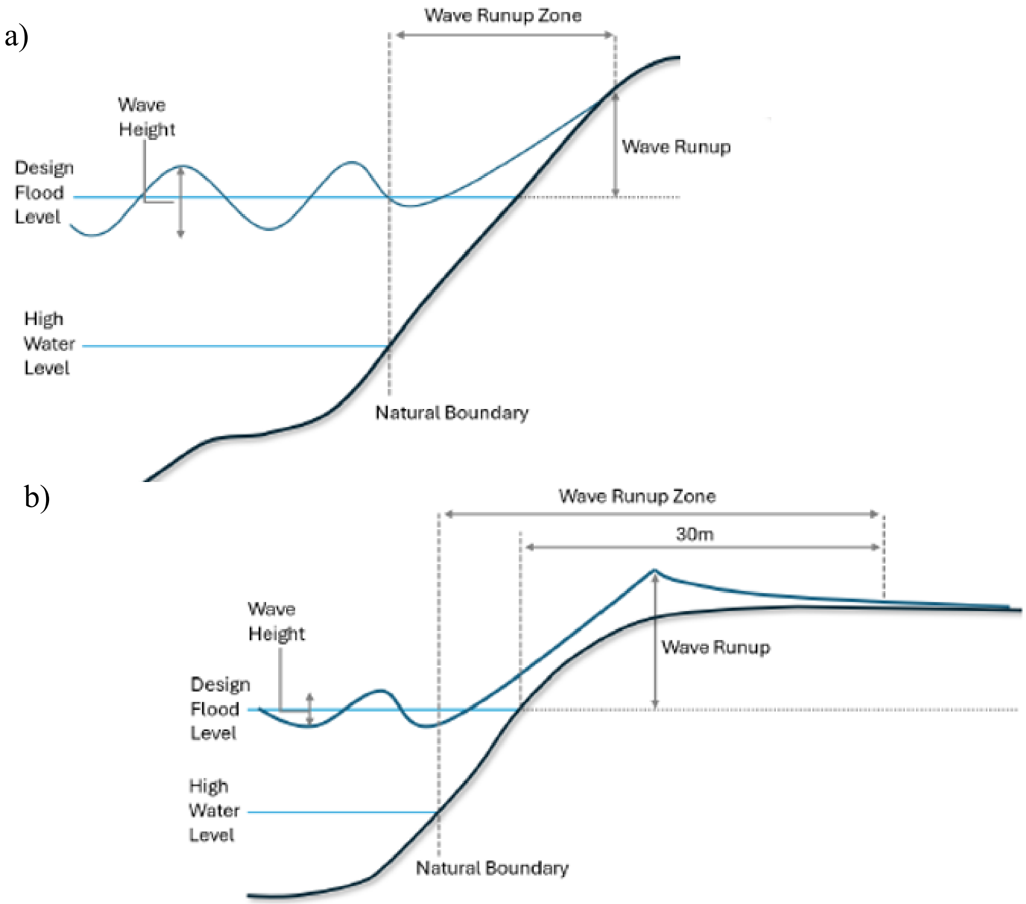

Figure 3: Illustrations of shoreline profiles showing a) continuous sloping foreshore (top panel) and 2) low-gradient bench (bottom panel)

3 MAPPED RESULTS

An example of mapped wave run-up along a section of the Shuswap Lake shoreline is shown in Figure 4. The example focuses on Blind Bay, a recessed embayment located along the mid-lake shoreline, the location of which is shown in Figure 2. The mapped output is presented as a series of shoreline segments corresponding to individual transects. For each segment, the landward extent of the shaded polygon represents the mapped flood extent, while the polygon colour indicates the calculated vertical wave run-up value ($R_{2}\%$). The values labelled along each transect line represent the corresponding FCL calculated at that location based on local wave and foreshore conditions.

The figure illustrates pronounced spatial variability in wave run-up along the Blind Bay shoreline. Shoreline segments located within the recessed portion of the bay exhibit relatively low run-up values (shown in lighter colours), reflecting limited effective fetch and reduced wave growth despite exposure to prevailing winds. In these areas, the orientation of the shoreline and the sheltered setting constrain wave development, resulting in lower wave run-up elevations.

In contrast, shoreline segments toward the outer margins of Blind Bay exhibit higher run-up values (shown in medium to darker colours). These locations are exposed to a broader range of wind directions, including westerly and northeasterly winds, and are associated with longer effective fetch lengths across the lake. As a result, larger waves are generated and propagate toward these shoreline segments, producing higher wave run-up elevations relative to more sheltered areas within the bay. Variation in run-up along similarly exposed shoreline results from the variability in shoreline slope and surface roughness. Adjacent transects subject to similar wave conditions can yield substantially different run-up elevations. Steeper foreshore slopes were generally associated with higher run-up, with the largest values occurring where slopes approached approximately 2H:1V.

Variability in wave exposure and shoreline results in irregular patterns of run-up and shoreline FCL. This differs from the consistent, linear increase in FCL typically observed progressing up a riverine flood map; and hence challenges the suitability of interpolation between adjacent FCL when applying floodplain maps to shoreline locations between two FCL isolines. Instead, it has been recommended that the higher of the two adjacent FCL values is applied for locations between shoreline FCL isolines.

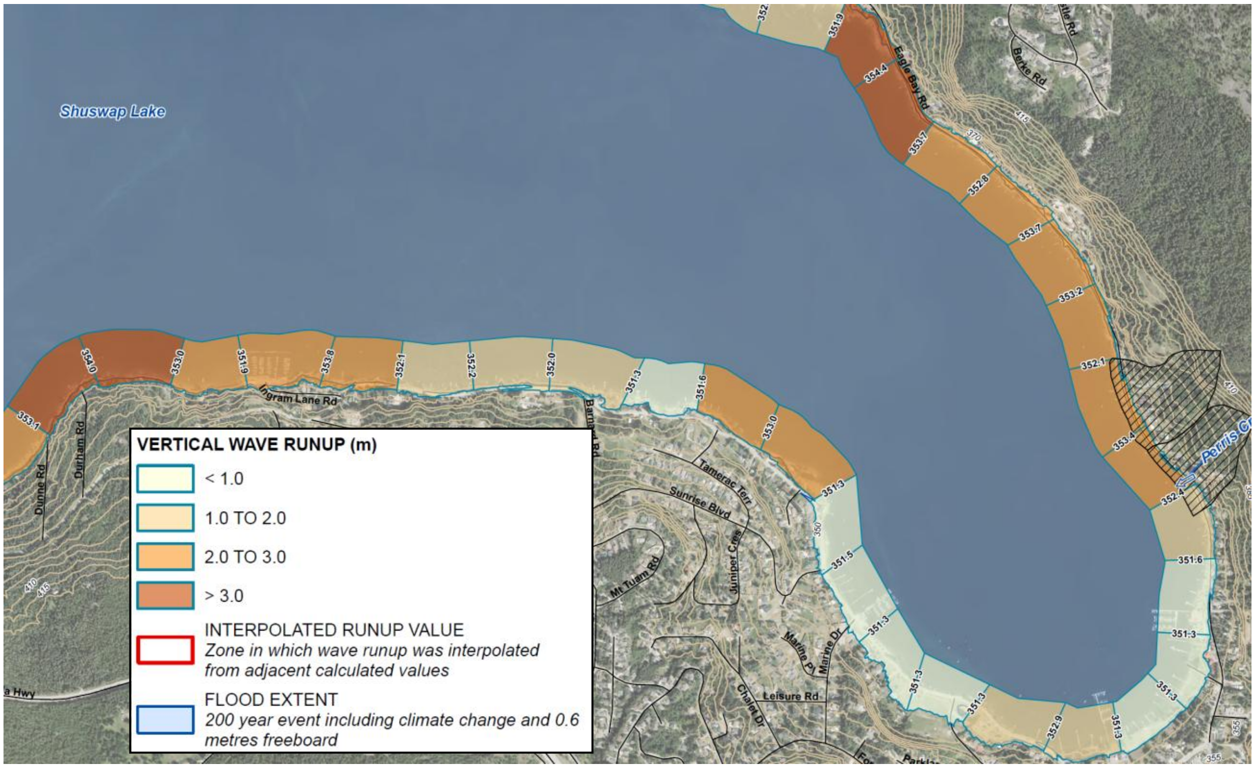

Figure 4: Example of mapped wave run-up on Shuswap Lake

4 CONCLUSION

This paper presented an applied approach for incorporating wave run-up into regional floodplain mapping of shoreline environments, demonstrated using lakes within the Shuswap Region. Wave run-up was estimated along regularly spaced shoreline transects using empirical formulations and combined with design still water levels, wind setup, and adopted freeboard to define flood construction level (FCL) elevations. The resulting wave-affected flood extents were mapped as spatially explicit polygons along the shoreline, supporting interpretation of wave-related flood hazards for land use planning.

The approach is efficient, repeatable, and suitable for application at a regional scale relative to phase-resolving wave models. Spatial resolution can be increased, where warranted due to complex shoreline geometry or development pressure, by reducing transect spacing. By explicitly representing spatial variability in wave exposure and run-up, the method provides increased value and greater transparency for property owners and land use planners than floodplain mapping approaches based on uniform run-up or freeboard allowances.

Several limitations and residual risks remain inherent to the approach. Empirical run-up equations rely on simplified representations of shoreline conditions and may overpredict run-up where the infinite-slope assumption is not realized, particularly in areas with low-gradient benches, berms, or engineered shoreline features. The method does not resolve overtopping, ponding, or dynamic inland flow processes, sub-transect spaced variability, or future changes in shoreline geometry or materials.

Accordingly, while the approach provides a consistent and defensible basis for regional floodplain mapping and planning-scale decision-making, residual risk remains at specific sites. Site-specific assessments may be warranted in locations where shoreline conditions substantially deviate from those represented by the transects, where development sensitivity is high, or where more detailed evaluation of wave processes is required to support design or risk management decisions.

5 ACKNOWLEDGEMENTS

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