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TSUNAMI VULNERABILITY ASSESSMENT OF CANADIAN WEST COAST COMMUNITIES BASED ON EVACUATION CAPABILITY

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ABSTRACT

The Canadian Pacific coast is located in a highly seismic region with active convergent plates with the potential to generate large tsunamis. The tsunami vulnerability of communities in British Columbia is assessed using geographical information system (GIS) model for potential run up heights between 3-25 m and the difference between the necessary pedestrian time to safety and the tsunami arrival time, defined as the available time (AT). Using these metrics, 8 communities were identified to be highly vulnerable to tsunami due to run ups of 25 m: Ucluelet, Gordon River 2 IRI, Tofino, Esowista 3 IRI, Hesquiat 1 IRI, Hope Island 1 IRI, and Masset and Masset 1 IRI. The high vulnerability level was considered when the AT was less than 15 min. Tofino and Ucluelet were assessed to be particularly vulnerable given that they are resort communities where high number of tourists during peak seasons. Additionally, many large tourist accommodations are located near the shoreline, which are high-risk regions. The majority of the BC population is located in the low vulnerability regions of the Strait of Juan de Fuca and Georgia. Delta and Richmond were determined to have negative ATs as the majority of their communities are located within low-lying areas, but these areas are highly vulnerable to tsunamis caused by landslides. This study highlights the need for reliable run-up modelling in high vulnerability regions, which is currently lacking throughout British Columbia.

Keywords: Tsunami, vulnerability, risk, run up, evacuation, inundation zone, GIS

1. INTRODUCTION

The Canadian Pacific coast is located in high seismic region as a result of the many active faults that form part of the Pacific Ring of Fire. The largest tsunami threat is from the Cascadia Subduction Zone (CSZ), an active fault capable of generating M 9.0 earthquakes with a return period between 400-600 years. The CSZ is located along the Pacific coast from Vancouver Island to northern California. Geological evidence has been discovered throughout Vancouver Island, Washington, and Oregon of a great tsunami from the CSZ in 1700 (Clague, Bobrowsky and Hutchinson 2000; Jacoby, Bunker and Benson 1997). Run ups from this event are estimated to be approximately 5 m along the west coast of Vancouver Island and up to 15-20 m at the head of some inlets (Clague, Bobrowsky and Hutchinson 2000). The Pacific coast is also vulnerable to far sources in the Pacific Ocean such as the Aleutian trench, along the south coast of Alaska and Aleutian Islands. In fact, the largest tsunami in recent history to occur in the Canadian Pacific coast was in 1964 by the great Alaska earthquake. Port Alberni, located at the head of a long and narrow inlet making it prone to wave amplification, was the most severely affected. The tsunami caused no casualties in Canada and $10 million (1964 dollars) in damage. Coastal areas are also at risk of tsunamis caused by local shallow earthquakes and landslides, such as in 1975 in Katimat where submarine landslides caused run ups of up to 8.2 m in height (Clague et *al.*, 2001). The majority of the fiords in British Columbia contain unstable sediments that caused the 1975 landslide and are at risk of similar events today. Tsunamis caused by landslides are not within the scope of this study. An assessment of the tsunami hazard for the Canadian Pacific coast by Leonard and Rogers (2015) suggests a probability of run ups exceeding 3m, which has the possibility of causing significant damage, between 10-30 % in 50 years.

1.1 Study Area

The study area is the Canadian Pacific coast, which results in the coastline of British Columbia (BC). All municipalities located within 4 km of the coast or inlets were included, totalling 172 communities and approximately 3 million residents. Most of the residential population is located in the large urban centers, including Victoria and Vancouver, and in the Strait of Juan de Fuca and Strait of Georgia (Figure 1). However, the residential population is likely underestimated as 105 communities are Indian Reserves (due to cultural sensitivity, hereafter to be referred to as Reserves or IRI), which are not obligated to participate in the census, of which 15 have a population of 5 and below, resulting in some suppressed data (AANC 2013).

1.2 Zones – Warnings

The province of British Columbia in partnership with the U.S. National Tsunami Warning centers monitor for potential tsunamis. To effectively communicate a potential threat to the population, the province has divided the coastline into 5 zones: A, B, C, D and E (Figure 1; Emergency Management BC 2013). As these zones were devised to represent regions with a similar hazard, they are used in this study to categorize the communities at risk. Zone A and B were amalgamated to represent Haida Gwaii and the north coast. Zone C is the west coast of Vancouver Island, zone D is the Capital region (Victoria and vicinity), and zone E is the metropolitan region of Vancouver and surrounding communities.

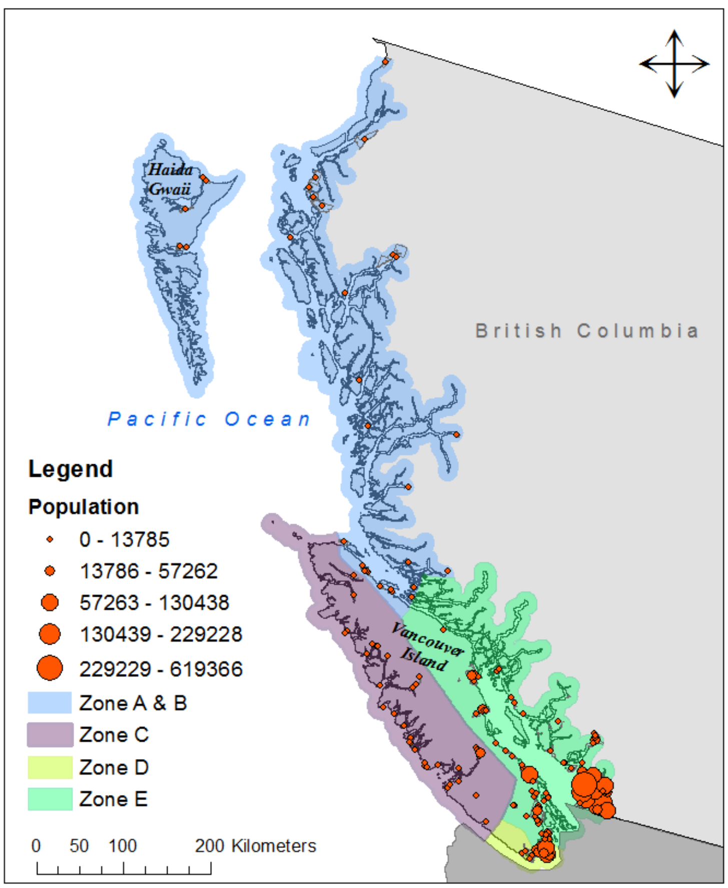

Figure 1: Tsunami zones and population distribution of British Columbia (modified from Emergency Management BC (2013))

2. METHODOLOGY

2.1 Run-up calculations

The hazard zone (HZ) and safe areas (SA) were computed for run ups between 3 m and 25 m, with a 2 m interval. The SA was computed by first eliminating all areas with elevations equal to or lower than the run up value. To eliminate small gaps in the SA produced as artefacts from processing the DEM, the SA were shrunk 4 cells and expanded 3 cells. To create a uniform HZ extending to the primary run up extent, as typically done in evacuation mapping (Port Hardy 2015; Alberni-Clayoquot Regional District 2015; Village of Masset 2013), SA less than 8 cells (3,283.74 m^2 in UTM projection) located within the main HZ were eliminated. Unless these small SA are specifically identified, it is uncertain that residents will utilized them to escape to safety. Additionally, these small SA have a potential to be overtopped even though their elevation is above the run up value as they are located closer to the shoreline (FEMA, 2002). This provides a conservative assessment of the HZs. The HZ was computed as the inverse of the SA. A 30 m digital elevation model (DEM) was used consistently throughout the model.

The surface area of the HZ is used to estimate the resident population by multiplying it with the population density of each community using census data. The tourist population was not included in the scope of this study, as no reliable database currently exists in British Columbia quantifying this value.

2.2 Available time

The available time (AT) is defined as the time necessary to reach safety less the arrival time of the first tsunami and when the first tsunami wave arrives. Conversely, a negative value represents the amount of time a resident would have needed to reach a safe area after the first wave arrives.

The necessary time to safety is computed by calculating the Euclidian distance of each cell in the model (raster) located in the hazard zone to the nearest safe area and then dividing by the travel speed. A bear-earth model was used to calculate the distance to safety. Two velocities were used for the analysis: mobility-impaired ambulatory speed, taken as 0.89 m/s (FEMA 2012); and an average adult walking speed of 1.22 m/s (Wood and Schmidtlein 2013). Vehicle based evacuation was not considered in this analysis as pedestrian evacuation is considered the most efficient in most cases, as the sudden influx of vehicles on the road is likely to cause traffic jams (Johnstone and Lence 2012). Additionally, the road network is likely to be damaged following an earthquake, further diminishing vehicle-based evacuation efficiency. The tsunami arrival time was taken as the publicly available information from the Province of BC (Table 1) and interpolated for communities where the information was not available.

Table 1: Arrival time in minutes of the first tsunami wave of various communities in British Columbia (BC Earthquake Alliance 2016)

Location	Arrival time of first wave (min)	Location	Arrival time of first wave (min)
Tofino	20	Esquimalt Harbour	70
Ucluelet	25	Victoria’s Inner Harbour	75
Winter Harbour	30	Sidney	120
Port Renfrew	35	Fulford Harbour	125
Bella Bella	40	Boundary Bay	130
Sooke Harbour	55	Delta/Richmond	135
Gawaii Haanas,	55	Burrard Inlet	150
Haida Gwaii	55	Nanaimo	155
Port Alberni	65	Prince Rupert	170

The duration of the earthquake and the reaction time of residents are not included in the AT. Safety measures in BC direct residents to leave for safe grounds after a strong earthquake, and to not wait for the tsunami warning. Despite this, it is expected that factors such as recognition of the hazard, evacuation warning infrastructure and one’s wish to collect valuable items will affect the evacuation departure time of a segment of the population (Park, et al. 2012).

For these reasons, high vulnerability is defined in this study as communities with a minimum AT of 15 min or less, moderate vulnerability between 16 and 30 min, and low above 30 min.

3. RESULTS

As the arrival time differs greatly between locations, the HZ surface area and population exposure is not a good metric to represent the vulnerability of communities. Instead, the distribution of the minimum value of the available time (AT) of each community is plotted as a function of the run up (Figure 3). A minimum run up of 3 m is used as this represents the threshold of significant damaged with high probability of occurring in Canada (Leonard and Rogers 2015).

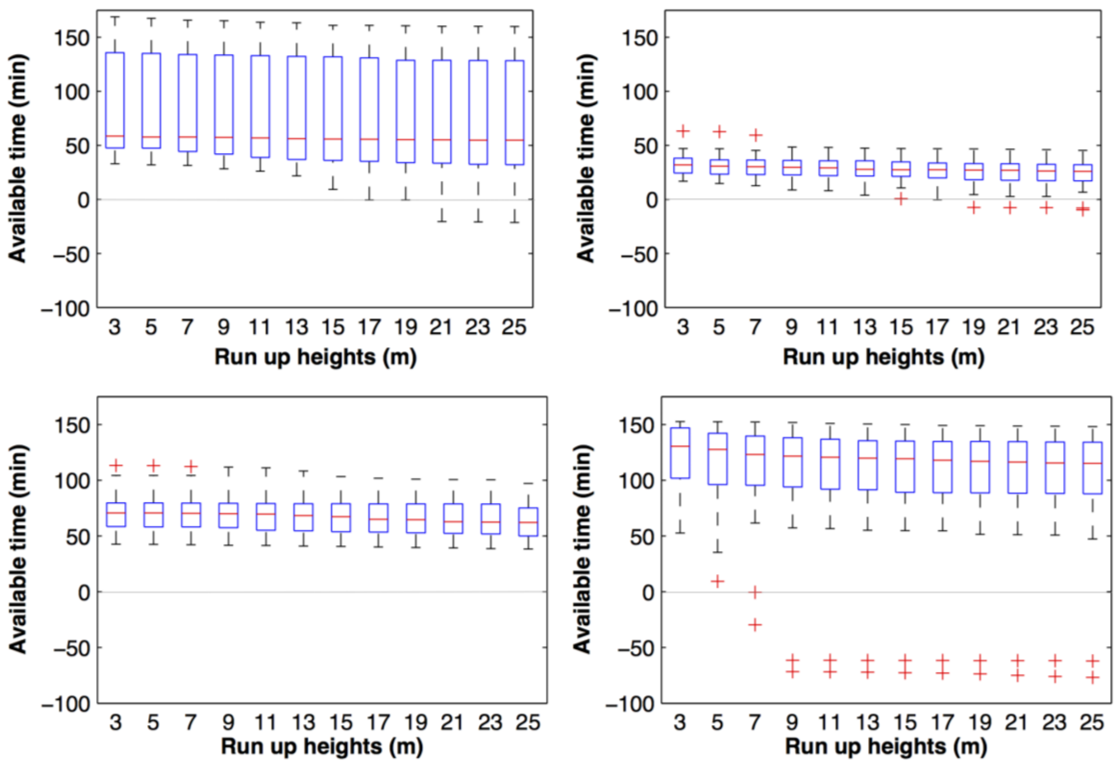

Figure 2: Minimum available time (AT) of all BC communities for run ups between 3 m and 25 m: (a) zone A and B; (b) zone C; (c) zone D and; (d) zone E. Note that the red lines represent the mean values.

3.1 Zone A and B

Zone A and B have the most elongated boxes as two distinct dataset are present, municipalities of zone A and zone B. The median zone A and B are above 50 min at all run up, zone A and B individual AT average is of 42.2 min and 145.4 min respectively. The minimum value reaches 0 at 17 min where as lower bound of the 25th percentile never goes below 30 min for any run up. Zone A has no outliers, but the lowest values are Masset and Masset IRI, which are located next to each other, in the north of Haida Gwaii. This zone has the second lowest residential population but the lowest population percentage at 25 m run up of 29% (Figure 4), totalling 11,727. The area in the HZ increases steadily with run up, having the largest increase of 3.6 and 3.3% at 11 and 15 m run ups, respectively. The communities within this zone have a low vulnerability up to 7 m run up. At 25 m run up, 3 and 4 communities are considered high and moderate vulnerabilities, respectively, out of a total of 33.

In Zone A and B, Port Hardy's and Masset's current tsunami evacuation maps indicate a HZ corresponding to a run up of 10 m. The ATs of these communities for such a run up are 30.8 and 34.8 min, respectively. Run ups between 6 m and 13 m were recorded on the seaward side of the southeast tip of Haida Gwaii in 2012 (Table 2). Masset, located on the northern tip, is slightly sheltered therefore it is reasonable to assume a value of 10 m. However, no numerical models have been developed for the north coast of BC, therefore the tsunami hazard and potential run up height is uncertain.

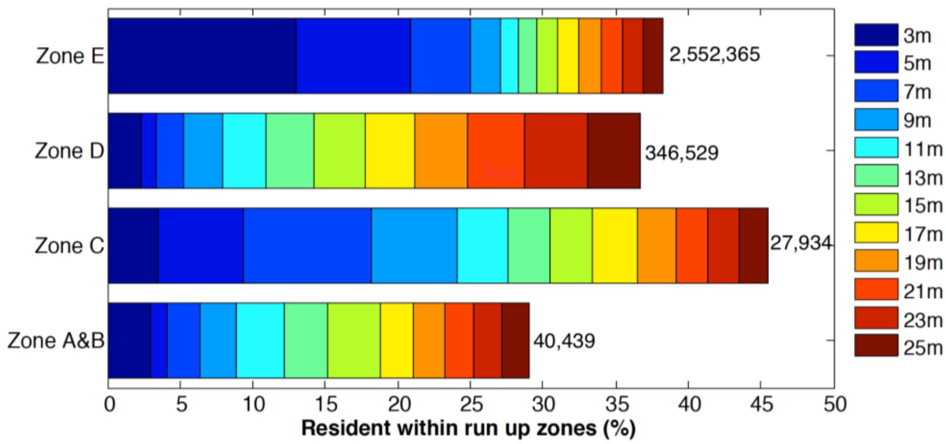

Figure 3: Percent of residential population within the tsunami inundation zone (HZ) for run ups between 3 m and 25 m; total population of each zone presented at the end of the bar

Table 2: Run up and planning run up values categorized by tsunami notification zones

Zone	Source	Type	Location	Run up (m)	Planning run up (m)
A	(Cassidy, Rogers, & Hyndman 2014)	H	Moresby Island	6.0-13.0	9.0-20.0
A	(Village of Masset 2015)	PL	Massett	6.7	10.0
B	(Port Hardy 2015)	PL	Port Hardy	6.7	10.0
C	(Aecom, 2013)	NM	Port Renfrew	3.0	5.0
C	(City of Port Alberni 2015)	H & PL	Port Alberni (Planning & 1700)	-	20.0
C	(City of Port Alberni 2015)	H	Port Alberni (1964 Alteutian)	6.0	9.0
C	(Aecom 2013)	NM	Port Renfrew	4.0	6.0
D	(Aecom 2013)	PL	Capital Region	2.65	4.0
E	(City of Vancouver 2011)	PL	Vancouver	1.3	2.0
E	(Clague and Orwin 2005)	PL	North Vancouver West Vancouver	1.5-2.5	3.75

H = historical data, NM = numerical model, PL = planning level
Planning run ups are the run up values with a safety factor of 1.5 used by communities as part of their evacuation plans

3.2 Zone C

A total of 39 communities are located in zone C. This zone has the lowest ATs, with an average value of 27.6 min (Figure 3). This zone also has the lowest ATs at the starting run up of 3 m of 16.9 min. The first instance of a community reaching life safety AT (AT of 0) is an outlier at 15 m. Following this, the ATs continuously decreases to reach a minimal value of -9.6 min at a run up of 25 m. The maximum residential population in the HZ is 12,710, representing 45.5%, the highest percentage of the zones (Figure 4). The population in the HZ grows 20% between 3 and 9 m. For run ups between 3 and 25 m, 0 to 21% of the communities have high vulnerability and 45 % have moderate vulnerability.

A run up of approximately 6 m in Port Alberni was observed during the 1964 Aleutian Earthquake and an estimated 20 m from the 1700 Cascadia event (Table 2). These values provide a worst-case scenario for Zone C, but due to the location of Port Alberni at the head of the Alberni inlet where wave heights are amplified, it may be an overestimation for the zone. Comparatively, a CSZ model established a run up of 4.0 m at Port Renfrew, 6.0 m including a safety factor (Aecom 2013). The Cherniawasky et al. (2007) CSZ model calculated waves between 6-9 m in Ucluelet, with a maximum of 15.7 m, but these waves did not propagate inland. At a run up of 20 m, 5 communities have high vulnerability (Tofino, Hesquiat, Tin Wis 11 IRI, Gordon River 2 IRI, and Ucluelet) and 13 have moderate vulnerability. Using the lower historical run up value of 6m leaves only Tofino as highly vulnerable.

This area is highly populated by tourists during some seasons, with two of its municipailites, Tofino and Ucluelet, classified as resort communities. During peak tourist seasons, these communities' populations can increase up to 60% (Johnstone and Lence 2012). Tourists can be particularly vulnerable to natural hazards as they may not be well educated in local emergency procedures. Additionally, a large percentage of tourist accomodations and tourist attractions are located near the shoreline; the most vulnerable area.

3.3 Zone D

The lower bound of the AT of Zone D decreases almost linearly between 42.6 and 38.3 min, with an average of 57.0 min. The maximum residential population within the HZ is 127,176. The percent of its area and population within the HZ also increases linearly, with the exception at a run up of 5 m, which causes a minimal increase, similarly to Zone A and B (Figure 4).

A far-field tsunami would need to travel the Strait of Georgia, between the Vancouver Island and Washington State before reaching Zones D and E, which explains the large arrival times in these areas. Numerical models performed in this extent demonstrate that energy of the waves attenuate in this area (Aecom 2013; Cherniawasky, et al. 2007). Run ups of 4.0 m, including the safety factor were established in this region (Table 2). All the communities within this zone have a low or moderate vulnerability at a run up of 25 m, and all have a low vulnerability at 5m run up. The results for this zone suggest a very low tsunami risk.

3.4 Zone E

Zone E has the highest minimum AT, ranging from 65.8 to 47.3 min with an average of 59.9 min. The communities of Richmond and Delta are outliers in the Zone E dataset. They have the overall lowest AT, reaching their peak at run ups of 9 m. Zone E is the most populated zone, as it includes the metropolitan area of Vancouver. At the peak run up of 25 m, a maximum of 977,555 (38.3%) of the population is located in the HZ. However, depending on the run up, Delta and Richmond contribute 40-60% of those values. Both communities have large rural areas within their municipal boundaries; therefore, using a population density based on the total surface area likely overestimates the residents located within the HZ. Not including Richmond and Delta, 100% of the communities within this zone have low vulnerability.

There is no evidence of past tsunamis for the Strait of Georgia, implying that the 1700 Tsunami caused run ups of less than 1m in this region (Clague, Bobrowsky and Hutchinson 2000). The City of Vancouver defines their tsunami HZ with a run up of 2 m above high tides, whereas North and West Vancouver uses a run up between 1.5 and 2.5 m (Table 2). Adding a safety factor of 1.5 to these values yields a maximum planning run up of 3.75 m, below the maximum run up of 5 m to maintain life safety (AT above 0).

In addition, sea dikes for coastal flooding caused by severe storms and high tides protect the Vancouver metropolitan area. These structures may help militate against tsunami waves, but a strong earthquake could cause these dikes to fail. Even without structural failures, there is a possibility of dikes being overtopped in a worst-case scenario; high tides in addition to high tsunami waves. Even with this worst-case scenario, Zone E has low vulnerability to tsunamis, as ATs are high at high run up values.

3.5 High risk area

The high risk area is defined as that with an AT less than 15 min. The evolution of available times for communities with high vulnerability at the maximum run up is shown in Figure 5 for a mobility impaired and average adult ambulatory speed of 0.89 and 1.22 m/s, respectively. A total of 11 communities fit this criterion, but Tin Wis 11 IRI was not included as its population is listed as 0 in the census and is located within the Municipality of Tofino. Zone C has the largest high-vulnerability communities (Ucluelet, Gordon River 2 IRI, Tofino, Esowista 3 IRI, and Hesquiat 1) followed by Zones A and B (Hope Island 1 IRI and Masset and Masset 1 IRI). All communities, other than Hope Island I IRI, have 80% of their community located within the HZ at 25 m run up (Figure 5). The at-risk population has a linear correlation with the area within the HZ as the population is calculated with this value multiplied by the population density.

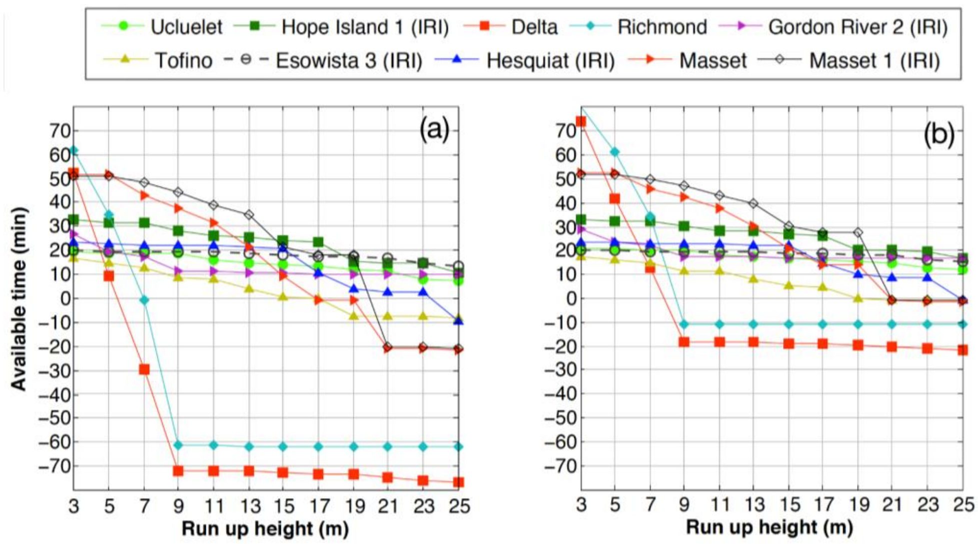

Figure 4: Available times for high-vulnerability municipalities at run up of 25 m: (a) mobility impaired ambulatory speed of 0.89 m/s; and (b) average adult ambulatory speed of 1.22 m/s

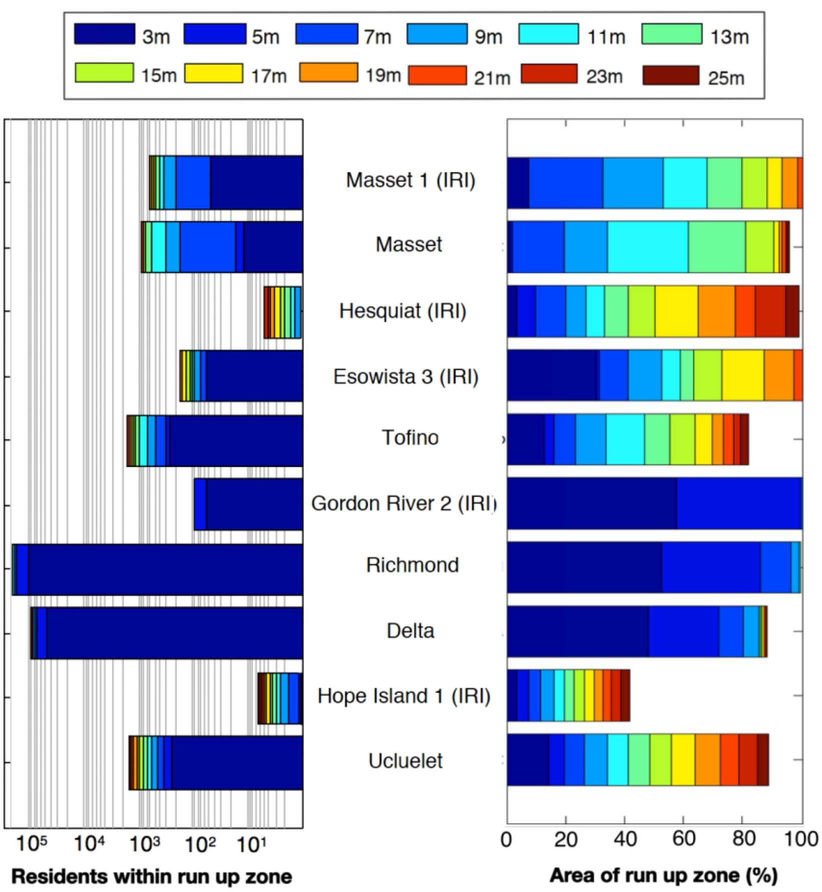

Figure 5: Communities residential population and percent of its area within the run up zone (HZ)

Communities located in Zone C could feasibly experience run ups of 20 m. Low-population communities such as Gordon River 2 IRI, Esowista 3 IRI, and Hesquiat 1 IRI have at least 80% of their area and population within the HZ at this run up level. Using an adult ambulatory speed, the AT of Esowista, Hesquiat and Gordon River are 18.2, 9.3, and 16.9 min, respectively (Figure 4). The entire community of Gordon River is located within the HZ at run ups of 5 m (Figure 5).

Although Tofino doesn't have the lowest AT, it is the most vulnerable community. The topography and geometry of the Esowista Peninsula, elongated shape with the highest elevated area at the far north tip, causes very long distances to travel to safety with low run ups (Figure 7). Tofino has high vulnerability at run ups of 5m. Using the average walking speed of an adult, the AT reaches below 15 min at 7m run up; instead of 5m using the mobility impaired ambulatory speed. Similarly, the AT reaches 0 at 19m instead of 15m run up. Tofino's residential population is approximately 2,000. Fortunately, the region with the highest population density is in the village, which is mostly located within the SZ (red area at the far left of Figure 6). However, as a resort community, its population increases substantially during the summer. Most large tourist accommodations are located on the seaward side of the peninsula in the most hazardous regions, identified as the resorts in red circles (Figure 7). Ucluelet is located a short drive southwest of Tofino, in the Ucluth Peninsula. Similarly to Tofino, Ucluelet is a resort-community also with an elongated shape with most of the resorts located along the shoreline. However, its ATs is never less than the life safety threshold, reaching a minimum of 7.6 and 12.1 min using mobility impaired and average adult ambulatory speeds, respectively. Ucluelet has higher AT than Tofino as its topography creates pockets with elevations above 25 m throughout the Peninsula, creating multiple safe heavens. Even with these areas, Ucluelet has high vulnerability. A potential mitigation strategy for these communities to reduce the tourist population at risk located in these high risk regions would be add vertical evacuation shelters near the shoreline.

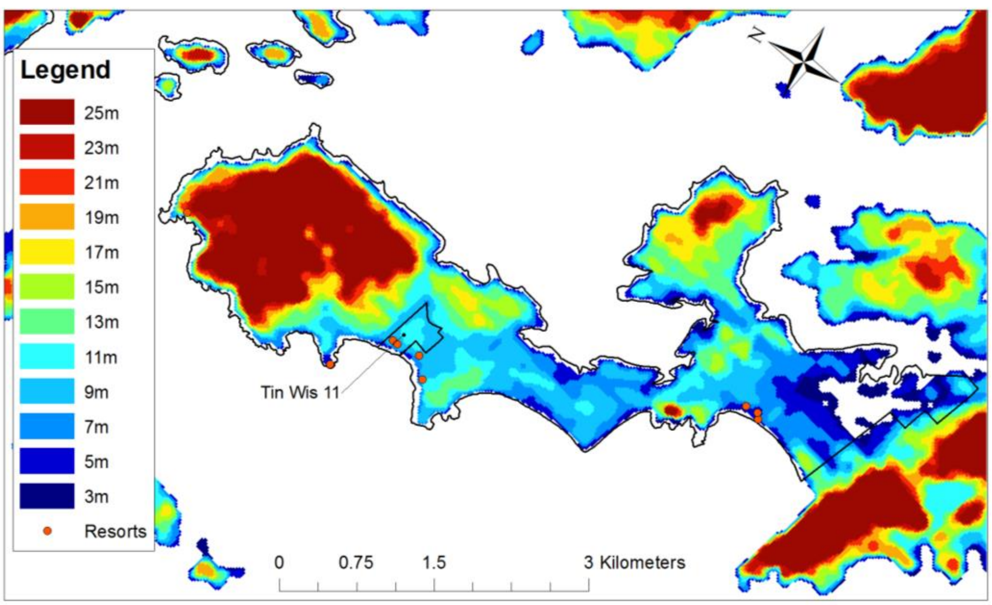

Figure 6: Safe areas (SA) corresponding to run ups ranging from 3 m and 25 m for the Municipality of Tofino and Tin Wis 11 IRI, and locations of large resorts

The combined residential population of Masset and Masset 1 IRI is 1,510. Masset reaches the life safety threshold at a run up of 17m using a mobility impaired ambulatory speed, and at 21m using an average adult walking speed (Figure 4). At a run up of 13m which is the higher end of the recorded run ups in Haida Gwaii in 2012 (Table 2), both of these communities are 80% in the HZ (Figure 5) and have an AT between 21.8 and 40.0 min, respectively. If a realistic run up value for these communities is between 10 and 13m, Masset and Masset 1 IRI have moderate tsunami vulnerability.

Delta and Richmond are the most populated communities and have the lowest ATs, reaching the life safety threshold slightly after 5m and 7m run up respectively using mobility impaired ambulatory speed. Using an average walking speed, the life safety threshold is reached in Delta at 7.8m and 8.5m in Richmond, an improvement of 2.4 and 1.6m in run ups values. For Delta, at a run up of 5m, 71.8% of the municipality's area is within the HZ, putting 72,800 residents at risk (Figure 5). Similarly at 7m run up, 96.6 % Richmond's area is in the HZ with 189,300 residents at risk. No sediments or geological evidence of indicating the occurrence of a past tsunamis has been found in the bogs of Delta and Richmond, confirming similar past studies (Clague, Hutchinson and Lesemann 2005). This suggests that past, and therefore potential tsunamis, caused only small run ups in the Strait of Georgia. Although both of these communities have large areas with high population in low laying areas, these communities have low vulnerability for a far-field tsunami due to low tsunami hazard. However, this risk assessment does not include locally generated tsunamis caused by landslides, as these would have much lower arrival times, and therefore lower ATs.

4. DISCUSSION

The travel time was calculated using a bare-earth model, where all land was considered equal, not considering the effects of travel speed slope and land cover (Wood and Schmidtlein 2013). The built environment in the distance to safety could increase or decrease the time to safety of the population depending on the circumstance. The even surface of roads and other built path can increase travel speed. Conversely though, pedestrians following roads may not take the most direct route. Built environment, such as large structures and fenced regions, could cause necessary detours for pedestrians, elongating their travel route. Some of the finer details in the topography are omitted due to the relatively coarse size of the raster of 30m used throughout the model. However, as a bare-earth model was used to find the minimal time to reach safety using the shortest distance possible distance on land, such fine details are not necessary. In addition, as the same topological dataset was used throughout the model, consistency was maintained for all communities. The duration of a preceding earthquake and reaction time of residents were not included in the time necessary to reach safety, adding additional conservatism to this parameter.

In identifying the hazard zone, communities should take great care in not overestimating the run up or add too great of a safety factor as this would increase the distance and time to safety. However, safe havens should be identified with a high level of certainty that they will not be inundated or overtopped, similarly to what occurred in some areas during the Tohoku Japan Earthquake (FEMA 2012). For planning purposes, sea level rise caused by climate change should be included in the run up; BC recommends planning for an increase of 1 m until 2100 and 2 m until 2200 (Sandwell 2011).

Tsunami mitigation strategies include structures (dikes and sea walls), land use planning, and vertical evacuation shelters. Sea walls and dikes are not always a cost effective measure for very large waves. Vertical evacuations structures should be considered in high vulnerability communities, such as Tofino and Ucluelet. Both are very similar communities in terms of tsunami risk, as both are resort-communities with many tourist accomodations located along the shoreline in high risk regions. Tourists can be particularly vulnerable to natural hazards as they may not be well educated in emergency procedures. Tofino requires additional safe heavens; its AT is negative for run ups of 15 m and greater, potentially lower than expected run ups. Resorts would be ideal locations for vertical shelters as they typically have large structures, are located in the highest risk regions and accommodate tourists, a significant portion of the population during peak seasons. As run up modelling is lagging in this region, and for Zone A and B, the expected run ups for most of BC are not well known.

5. CONCLUSION

Using the available time (AT) as the primary metric, 8 communities were determined to have high tsunami vulnerability: Ucluelet, Gordon River 2 IRI, Tofino, Esowista 3 IRI and Hesquiat 1 IRI located in Zone C and Hope Island 1 IRI, Masset and Masset 1 IRI, located in Zone A and B. Tofino and Ucluelet are particularly vulnerable as they accommodate a great number of tourists during peak seasons, with large tourist accommodations in high risk regions near the shoreline and low ATs. Tofino has an elongated low-lying area with negative ATs regions, meaning that a portion of the population will not be able to reach a safe elevation before the first tsunami wave arrives. These communities are excellent candidates for vertical evacuation structures.

As 98% of the population living on the west coast are located in the least vulnerable zones, D and E, the overall tsunami hazard for the population of BC is low. Zone E has the lowest vulnerability, followed by Zone D as most of their communities have an available time greater than 50 and 30 min, respectively at a run up of 25m. Tsunami waves are expected to be attenuated once they reach these locations. Although the ATs of Delta and Richmondare low, they have a low vulnerability as a tsunami is expected to cause run ups below 5 m and arrive after 2 hours. However, Zones D and E could be vulnerable to landslide tsunamis occurring near the Strait of Georgia. For this type of an event the arrival time would be greatly reduced, and the hazard and vulnerability would increase.

The most vulnerable areas of BC do not have reliable run up predictions from models. The models have been completed for the most populous regions of BC in the Strait of Juan de Fuca and Georgia. To reliably assess the risk of communities, further studies are necessary for ZoneS A, B, and C to provide the specific tsunami and run-up hazard.

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