CHAPTER 4 LAKESHORE FLOODPLAINS

4.1 Chapter Synopsis

The lakeshore floodplain for the Okanagan Basin is extensive with over 300 km of coverage including Okanagan, Wood-Kalamalka, Ellison, Skaha, Vaseux, and Osoyoos lakes. The extent of the lake inundation can be determined by projecting the design lake levels across the land. However, in order to determine appropriate flood construction values the effects of waves on the shoreline must also be considered. This is completed by examining wind patterns across the lakes for seasonal storm events and modelling the resulting waves that are generated for the various individual lakes. Wave effects on the shorelines such as wave runup elevations are then determined.

The wind data for the Okanagan Basin was collected from three stations: Penticton, Kelowna and Vernon airports. These stations were chosen as the airport records are longer than other anemometer records in the area and also because anemometers at airports are generally well placed and away from obstructions (buildings and trees) that create turbulence. An analysis of the available wind data was undertaken to determine the largest storms likely to occur during the extended flood season (March – August). These values were then taken and integrated into a spatially-varying synthetic wind field for the lakeshore floodplain.

The synthetic wind field was used as input to the wave models for the individual lakes. Each lake was modelled individually, and the results provide the input necessary to determine the seastate (wave heights, periods, and directions) and the extent of the wave effects (how far onshore the waves will go). Wave runup at the shoreline, as well as flood water inundation, is an important component of the overall flood construction level (FCL) necessary to identify the flood risk to structures adjacent to lake shorelines.

4.1.1 Limitations on the Lakeshore Floodplain Component of this Study

- Where climate station elevation information was missing, a standard station elevation of 10 m above ground was assumed.
- Bathymetric maps used for the lakes were often historic and possibly out of date, especially in the nearshore. To address this potential issue in the assessment of wave effects, NHC relied upon wave heights calculated in deeper water typically about 100 metres offshore of the shoreline since the interpolated bathymetry nearshore could be shallower/deeper than it is in reality.
- Wave effects will vary depending upon the specific shoreline geometry and development. However, the study project area is too large to undertake analysis of wave effects at the scale of individual properties. Instead, a single generalized shoreline slope was used for each shoreline zone designated for each lake. The generalized shoreline slope chosen was one that was among the steeper shorelines within each zone and was exposed to the wave effects from the lake. This approach generally results in a more conservative wave runup value; it is recognized that the wave runup will be overestimated for some individual properties. There is also the possibility the wave effects will be underestimated for some properties with seawall type structures due to runup being greater for vertical walls.

- It is assumed in this analysis that the future foreshore slope and beach materials will be the same as that of the existing (or present day) foreshore. Any changes to the foreshore geometry (slopes, location of structures such as seawalls, etc.) will change the wave runup and as a result the overall FCL for individual properties.
- The accuracy of the estimation of wave runup is limited by the bathymetry available for Lake Okanagan. Higher resolution bathymetry for the lake and data collection for the nearshore could improve the determination of wave effects on the shoreline and is recommended for site specific analysis.

4.2 Analysis of Observed Wind and Pressure

4.2.1 Wind Data

Hourly historical weather data was extracted from ECCC in the Okanagan Basin. Only stations with hourly data sampling intervals were considered in this analysis. Any stations with longer intervals between wind data records were not included. The station identification (ID), data interval, location, and elevation for the stations selected for the analysis are summarized in Table 4-1.

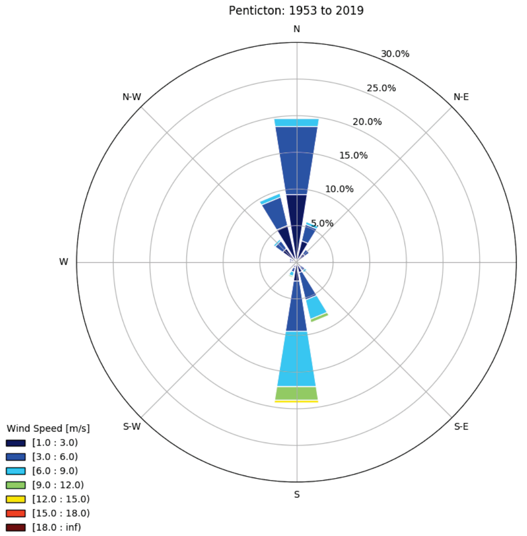
Table 4-1 Climate Canada Stations Information.

Area	Station Name	Station ID	Climate ID	Station location		Data Interval		Station Elevation (m)
				Latitude	Longitude	Start	End	
Penticton	Penticton A	1053	1126150	49°27'47.0	119°36'08.0	1953	2012	344.40
	Penticton A	50269	1126146	49°27'45.0	119°36'08.0	2012	2020	344.40
Kelowna	Kelowna A	1001	1123970	49°57'22.0	119°22'40.0	1959	2005	429.50
	Kelowna AWOS	30954	1123965	49°57'22.0	119°22'40.0	2004	2009	429.50
	Kelowna	48369	1123939	49°57'26.0	119°22'40.0	2009	2020	433.10
Vernon	Vernon CS	6837	1128581	50°13'23.9	119°11'36.8	1994	2008	482.00
	Vernon Auto	46987	1128582	50°13'23.9	119°11'36.7	2007	2020	482.00

4.2.2 Wind Rose Plots

The wind station's data for each area was combined and analyzed to generate rose plot diagrams which are shown in the following figures. The rose plots clearly show that surface level winds tend to align with the primary axis of the valleys in the region and that winds in general are light in this region.

Penticton – Primarily northerly (N) and southerly (S) winds, following the valley orientation at this location (Figure 4-1). Station located immediately south of Okanagan Lake. South southeasterly (SSE) and north northwesterly (NNW) winds are also recorded.



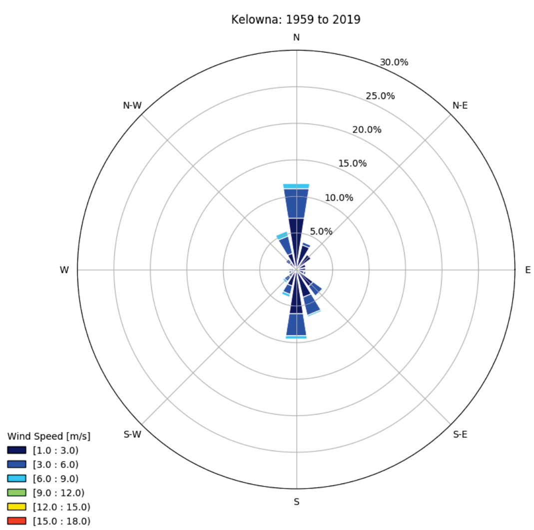
Wind Speed and Direction Frequency Distribution

	1 - 3	3 - 6	6 - 9	9 - 12	12 - 15	15 - 18	> 18	Total (%)
N	9.3	9.4	1.1	0.1	0.0	0.0	0.0	19.9
NNE	3.0	2.3	0.4	0.0	0.0	0.0	0.0	5.7
NE	1.4	0.7	0.1	0.0	0.0	0.0	0.0	2.2
ENE	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.7
E	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.6
ESE	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.4
SE	0.7	0.7	0.3	0.0	0.0	0.0	0.0	1.8
SSE	1.5	3.8	2.7	0.5	0.1	0.0	0.0	8.6
S	2.6	6.9	7.6	1.9	0.4	0.1	0.0	19.5
SSW	0.8	0.6	0.6	0.2	0.1	0.0	0.0	2.2
SW	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.8
WSW	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.6
W	0.7	0.3	0.1	0.0	0.0	0.0	0.0	1.1
WNW	0.7	0.3	0.1	0.0	0.0	0.0	0.0	1.1
NW	2.3	1.3	0.3	0.0	0.0	0.0	0.0	3.9
NNW	5.2	4.0	0.5	0.0	0.0	0.0	0.0	9.7
Total (%)	30.4	30.9	14.1	2.8	0.6	0.1	0.0	78.9

Total Hours: 587295
Total Observations: 586945
Missing Observations: 350
Calm Observations: 123617
Percent Missing: 0.1 %
Percent Calm: 21.0 %

Figure 4-1 Wind rose plot - Penticton station.

Kelowna - Primarily northerly (N) and southerly (S) winds (Figure 4-2). South southeasterly (SSE) and north northwesterly (NNW) winds were also recorded. Station is located west of Okanagan Lake, sheltered to the west by Mount Knox and McKinley Mountains. The valley and lake have similar orientation at this location. Wind magnitude might not be representative of the of the wind conditions over Okanagan Lake near Kelowna.



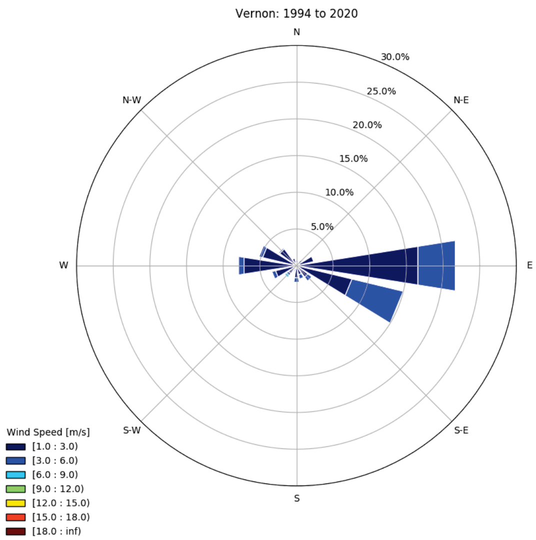
Wind Speed and Direction Frequency Distribution

	1 - 3	3 - 6	6 - 9	9 - 12	12 - 15	15 - 18	> 18	Total (%)
N	7.1	4.1	0.7	0.1	0.0	0.0	0.0	12.0
NNE	3.5	0.4	0.0	0.0	0.0	0.0	0.0	3.9
NE	2.5	0.1	0.0	0.0	0.0	0.0	0.0	2.6
ENE	1.4	0.1	0.0	0.0	0.0	0.0	0.0	1.4
E	1.3	0.1	0.0	0.0	0.0	0.0	0.0	1.4
ESE	1.1	0.3	0.0	0.0	0.0	0.0	0.0	1.4
SE	2.9	1.6	0.2	0.0	0.0	0.0	0.0	4.6
SSE	3.9	2.5	0.2	0.0	0.0	0.0	0.0	6.7
S	6.1	3.0	0.5	0.0	0.0	0.0	0.0	9.7
SSW	2.3	1.2	0.4	0.0	0.0	0.0	0.0	3.9
SW	1.3	0.7	0.3	0.0	0.0	0.0	0.0	2.3
WSW	0.7	0.3	0.1	0.0	0.0	0.0	0.0	1.1
W	0.7	0.2	0.0	0.0	0.0	0.0	0.0	0.9
WNW	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.6
NW	1.1	0.6	0.1	0.0	0.0	0.0	0.0	1.9
NNW	2.3	2.4	0.7	0.1	0.0	0.0	0.0	5.5
Total (%)	38.6	17.9	3.3	0.3	0.0	0.0	0.0	60.2

Total Hours: 532768
Total Observations: 456040
Missing Observations: 76728
Calm Observations: 165453
Percent Missing: 14.4 %
Percent Calm: 36.0 %

Figure 4-2 Wind rose plot - Kelowna station.

Vernon – winds predominantly easterly (E) and east southeasterly (ESE) (Figure 4-3). Westerly (W) winds were also recorded. Wind station located between Okanagan Lake and Lavington. O`Keefe and Commonage Mountains located west of the station. Wind sampled at this location follows the orientation of Lavington valley heading east towards Lumby, and directions are not expected be representative of the wind conditions at the northern end of Okanagan Lake.



Wind Speed and Direction Frequency Distribution

	1 - 3	3 - 6	6 - 9	9 - 12	12 - 15	15 - 18	> 18	Total (%)
N	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.7
NNE	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.7
NE	0.9	0.1	0.0	0.0	0.0	0.0	0.0	1.0
ENE	2.4	0.1	0.0	0.0	0.0	0.0	0.0	2.5
E	16.8	5.2	0.0	0.0	0.0	0.0	0.0	22.0
ESE	7.8	7.2	0.1	0.0	0.0	0.0	0.0	15.1
SE	1.9	0.7	0.1	0.0	0.0	0.0	0.0	2.7
SSE	1.3	0.6	0.0	0.0	0.0	0.0	0.0	1.9
S	1.6	0.6	0.0	0.0	0.0	0.0	0.0	2.3
SSW	0.6	0.2	0.1	0.0	0.0	0.0	0.0	0.9
SW	1.3	0.4	0.3	0.1	0.0	0.0	0.0	2.1
WSW	2.9	0.5	0.1	0.0	0.0	0.0	0.0	3.6
W	7.2	0.7	0.1	0.0	0.0	0.0	0.0	8.1
WNW	4.7	0.5	0.0	0.0	0.0	0.0	0.0	5.3
NW	2.8	0.2	0.0	0.0	0.0	0.0	0.0	3.1
NNW	1.0	0.1	0.0	0.0	0.0	0.0	0.0	1.1
Total (%)	54.3	17.3	1.1	0.2	0.0	0.0	0.0	73.0

Total Hours: 227616
Total Observations: 225796
Missing Observations: 1820
Calm Observations: 60792
Percent Missing: 0.8 %
Percent Calm: 26.0 %

Figure 4-3 Wind rose plot - Vernon station.

Peak Over Threshold Analysis

The peak over threshold analysis conducted for each station is based on a 12-hour interval between events for each predominant wind direction. The threshold values are listed in Table 4-2. Sensitivity of the results was assessed by changing the time interval to 24-hr. No variation was observed.

Table 4-2 Peak Over Threshold Analysis summary.

Area	Event	Wind Direction (˚)	Threshold Wind Speed (m/s)	Storm Duration (hr)
Penticton	Southerly	135-220	16.00	12
	Northerly	330-30	11.50	12
Kelowna	Southerly	135-220	10.95	12
	Northerly	330-30	11.00	12
Vernon	Westerly	240-320	5.50	12
	Easterly	60-135	6.00	12

Vernon station recorded westerly and easterly winds. Westerly events were assumed to co-occur with southerly event at Penticton and Kelowna. Similarly, easterly events were considered to co-occur with northerly events at Penticton and Kelowna. Concurrent southerly and northerly events at each station, and the corresponding wind speed and direction are summarized below and in Table 4-3 and Table 4-4, respectively.

4.2.3 Southerly Events

- Peak storms occur during the fall/winter season (October-February).
- At Penticton, the wind directions associated with storm events follows the valley orientation. Design wind direction: 180˚.
- Peak events at Kelowna are from an SSE direction (150-160˚). This is likely due to the station location west of Okanagan Lake. McKinley Landing and Ellington Mountains located between the station and the lake create a separate valley following an SSE orientation. For design, a SW-SSW wind direction has been chosen (2011 and 2019 events). Design wind direction: 190˚.
- Peak events at Vernon are from WSW direction (250-260˚), following west-east orientation of Lavington valley. It is assumed that wind directions over the north end of Okanagan Lake are aligned with the main valley for winds: 205˚ (based on Okanagan Lake orientation). The wind magnitudes were not adjusted, only the direction. It is unclear how representative the Vernon wind velocity measurements are with respect to wind velocity over the lakes.
- No information of the elevation of Penticton wind station was available and a standard station elevation of 10 m above ground was assumed. Elevation corrections were therefore not applied to design wind speeds. Over land to over water wind speed adjustments were not applied as both southerly and northerly 200-year design events have a magnitude greater than 18.5 m/s (correction factor <1).

Table 4-3 Historical southerly events.

Penticton			Kelowna			Vernon		
Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)
1963/10/21/4	22.2	180	1963/10/21/13	15.6	160			
2001/12/15/21	18.1	190	2001/12/15/23	11.4	150			
1963/10/24/6	17.8	180	1963/10/24/7	13.3	160			
1996/12/4/17	16.9	180	1996/12/4/11	12.2	150			
2008/11/21/22	16.4	190	2008/11/21/17	11.4	140			
2009/11/19/1	16.4	190	2009/11/19/22	12.8	150			
2012/1/24/20	16.4	190				2012/1/25/7	5.3	250
2014/2/12/5	16.1	190				2014/2/13/14	5.6	260
			2011/4/11/14	11.4	210	2011/4/11/13	6.1	250
			2016/3/10/12	14.4	190	2016/3/10/14	6.1	250

4.2.4 Northerly Events

- Peak storms occur during the fall/winter season (September-April).
- At Penticton, the wind directions associated with storm events follow the valley orientation. Design wind direction: 0˚.
- At Kelowna wind directions associated with storm events follow the valley orientation. Design wind direction: 0˚.
- Peak events at Vernon are from ESE direction (110˚), following east-west orientation of Lavington valley. Design wind direction: 20˚ (based on Okanagan Lake orientation).
- No information of the elevation of Penticton wind station was available and a standard station elevation of 10 m above ground was assumed. Elevation corrections were therefore not applied to design wind speeds. Over land to over water wind speed adjustments were not applied as both southerly and northerly 200-year design events have a magnitude greater than 18.5 m/s (correction factor <1).

Table 4-4 Historical northerly events.

Penticton			Kelowna			Vernon		
Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)	Date y/m/d/h	Wind Speed (m/s)	Wind Direction (˚)
1971/10/13/12	16.1	360	1971/10/13/11	11.1	360			
1959/4/23/10	15.6	20	1959/4/23/11	11.1	360			
1972/4/1/15	15.3	360	1972/4/1/14	13.3	350			
2012/1/10/8	15.0	350	2012/1/10/8	11.4	330			
1989/1/31/2	14.4	340	1989/1/31/11	12.8	350			
1991/10/21/11	14.4	350	1991/10/21/9	13.9	330			
1964/12/15/15	13.3	360	1964/12/15/16	11.7	340			
1974/9/26/7	12.5	330	1974/9/26/7	11.1	350			
2019/10/7/23	11.7	10	2019/10/7/22	15.3	340			
			2012/5/25/11	11.4	350	2012/5/25/23	6.1	110

4.2.5 Extreme Value Analysis

ARI events were calculated based on the peak over threshold analysis results, following the methodology summarized in Goda (2000) for data following a Gumbel distribution. ARI events and corresponding wind speeds are summarized in Table 4-5 for each station, for the site-specific predominant wind directions.

Table 4-5 ARI for design events at all wind stations.

ARI (years)	Penticton		Kelowna		Vernon	
	Northerly	Southerly	Northerly	Southerly	Westerly	Easterly
1	12.3	16.6	11.9	11.4	5.3	6.3
2	13.8	17.7	12.8	12.6	5.6	6.4
5	15.4	18.9	13.8	13.7	5.9	6.6
10	16.5	19.8	14.6	14.5	6.2	6.8
20	17.6	20.6	15.3	15.3	6.4	6.9
50	19.0	21.6	16.3	16.3	6.7	7.1
100	20.0	22.4	17.0	17.1	7.0	7.2
200	21.1	23.2	17.7	17.8	7.2	7.3

4.2.6 Atmospheric Pressure Data

Given the length of Okanagan Lake, it was deemed necessary to determine if a pressure gradient exists across the lake from the north end to the south end. The atmospheric pressure variation at the three stations was assessed to determine pressure probability distribution and variation of pressure during storms (record extremes) and calm weather. Based on the stations' elevations and comparison of records during storm and calm weather, the difference in pressure is not affected by wind magnitude or direction. Any pressure difference observed can be related to the difference in elevation of the stations. Thus, the data does not indicate there are strong pressure gradients across Okanagan Lake that could lead to significant differences in lake levels.

4.2.7 Seasonal Design Wind Event

Spatially-Varying Wind Field

Spatially-varying wind fields representative of northerly and southerly wind events were synthesized manually, by following the natural orientation of the lake and Okanagan valley. A spatially-varying wind field from an atmospheric model was considered for the basin, but extreme wind events during the flood peak times was not available for the dates that were available on record.

An example of Okanagan Lake's synthesized wind field shown in Figure 4-4. The details of the wind field are as follows:

- Wind Field Resolution: 2,500 m
- Width (x): 45,000 m
- Length(y): 120,000 m

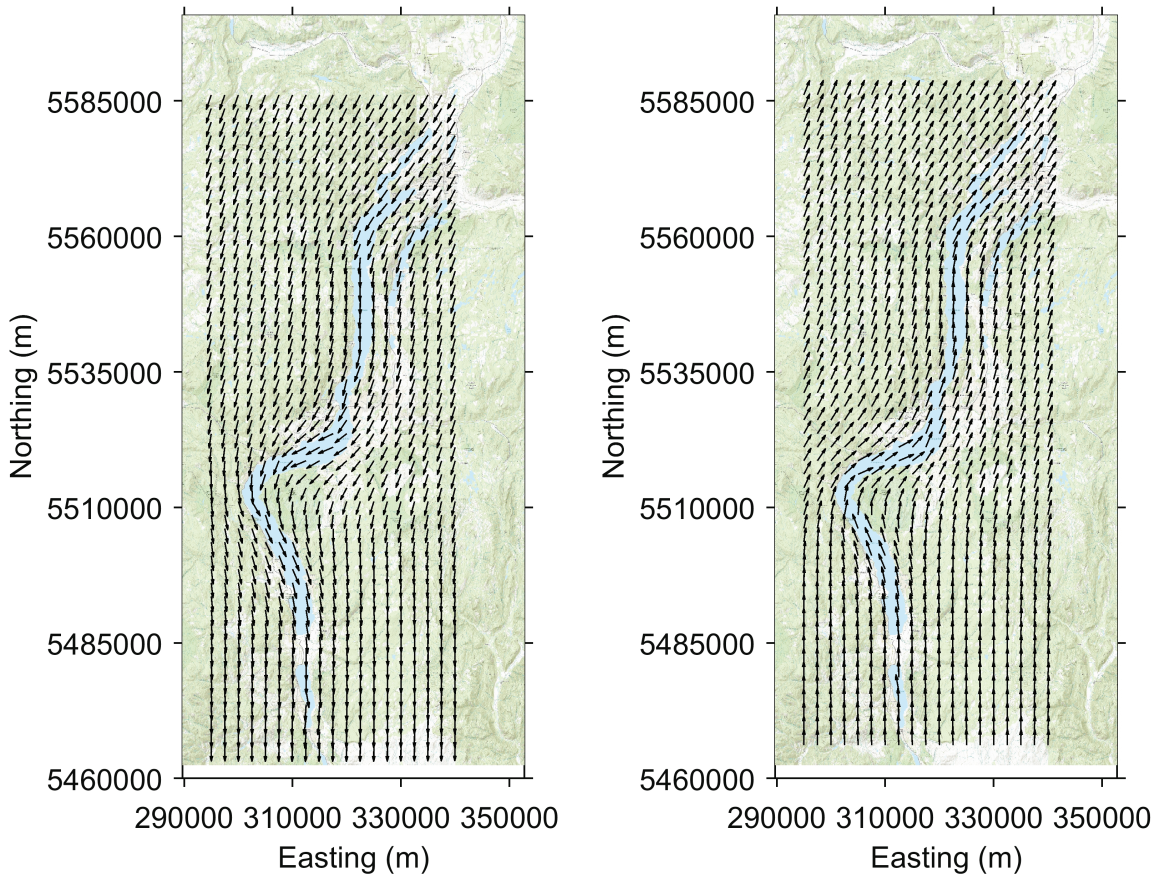


Figure 4-4 Synthesized wind fields for northerly (left) and southerly (right) events. Note that only the wind vectors over the lakes are used in the wave model analysis, and for this reason wind vectors away from the lakes are not relevant.

Analysis of Seasonal Extremes

The wind analysis was repeated for just the flood season (March – August) to determine wind magnitudes for a storm that was likely to occur during the actual times of flooding on the OLRS. The ARI events were calculated based on the peak over threshold analysis results for March -August, following the methodology summarized in Goda (2000) for data following a Gumbel distribution. ARI and corresponding wind speeds for flood seasons are summarized in Table 4-6. The thresholds are northerly 10 m/s and southerly 12 m/s. Storm event thresholds have been chosen such that at least 1 storm occurs every 2-3 years in the wind records. The Penticton location was chosen to represent the entire wind field as it has the highest seasonal winds.

Table 4-6 ARI of seasonal design events and confidence intervals for Penticton.

ARI (years)	Penticton					
	Northerly			Southerly		
	Wind Speed (m/s)	90% Confidence Interval Upper Bound (m/s)	90% Confidence Interval Lower Bound (m/s)	Wind Speed (m/s)	90% Confidence Interval Upper Bound (m/s)	90% Confidence Interval Lower Bound (m/s)
1	10.4	10.7	10.2	13.2	13.4	13.1
2	12	12.3	11.7	14.3	14.5	14.1
5	13.7	14.2	13.2	15.5	15.8	15.2
10	14.9	15.5	14.3	16.4	16.8	16
20	16	16.8	15.3	17.3	17.7	16.8
50	17.5	18.4	16.7	18.4	19	17.9
100	18.7	19.7	17.7	19.3	19.9	18.6
200	**19.8**	21	18.7	**20.1**	20.8	19.4

Comparison to Observation Data

A larger study on evaporation and development of a mass transfer model for water management purposes was conducted for Okanagan Lake by Spence and Hedstrom (2015). Three buoys were deployed across the length of Okanagan Lake for the duration of their study (July 2011 – May 2014). These buoys supported remote meteorological stations and were collecting wind data as part of the study. Wind Roses were developed based on the data they had collected at the stations and can be seen in Figure 4-5 below. The thick white line represents the relative frequency with which wind blows from each 10 degrees of compass direction. The red dots represent buoy locations. The wind roses show that the prevailing winds on the lake closely follows the orientation of the lake valley. These observations validate the decision to align the wind direction in the synthetic wind fields to the shape of the valley and the lake.

When considering magnitude, the largest storms are at Penticton from the south and occur primarily in winter (section Figure 4-6). The winds at Kelowna are much weaker than those at Penticton and calm during a greater percentage of time. The Kelowna airport is located in the next valley to the east and is sheltered by topography. As such, it is not representative of the winds over the lake. The Vernon wind station is located at the head of Kalamalka Lake, in the same valley as Kelowna airport and similarly is not a good indicator of the winds over the lake.

Wind data for the overlapping period between Penticton airport station and weather buoy stations were examined. Several larger storm events (greater than 16 m/s at Penticton with an ARI of roughly a 1 year (Table 4-5)) occurred in this period with comparable data. Figure 4-6 shows the wind stick plots from one event (February 2014) with the four stations over the course of this event and several other small events after. The results show that the wind speeds measured at the buoys are less than those observed at Penticton during the peak of the storm, but they do share events with similar magnitudes across all stations. With limited data that is required to establish proper correction between stations and to err on side of caution, it is decided to use Penticton Airport data for the seasonal design wind event.

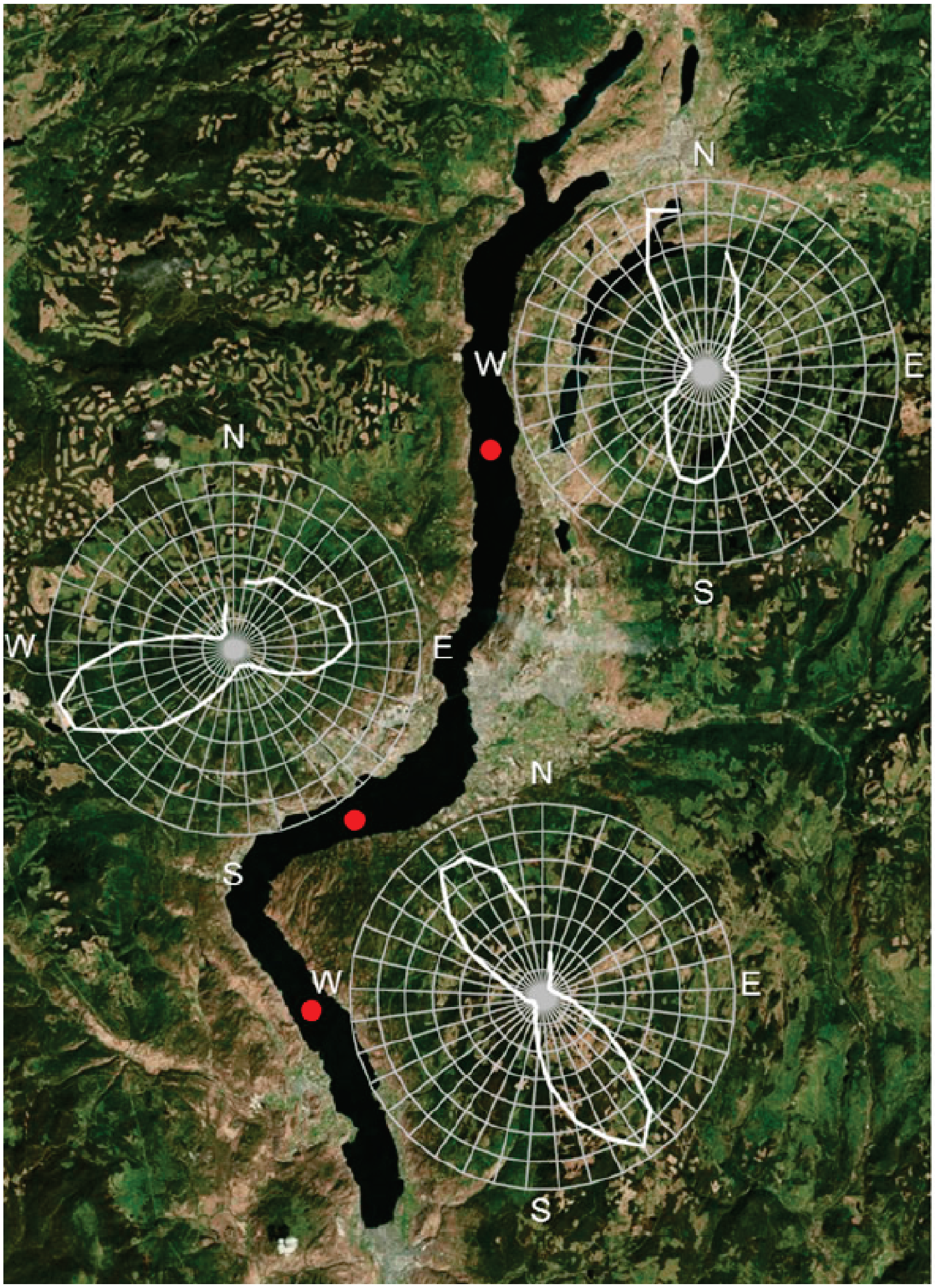


Figure 4-5 Wind roses from Spence and Hedstrom (2015)'s weather buoys on Okanagan Lake.

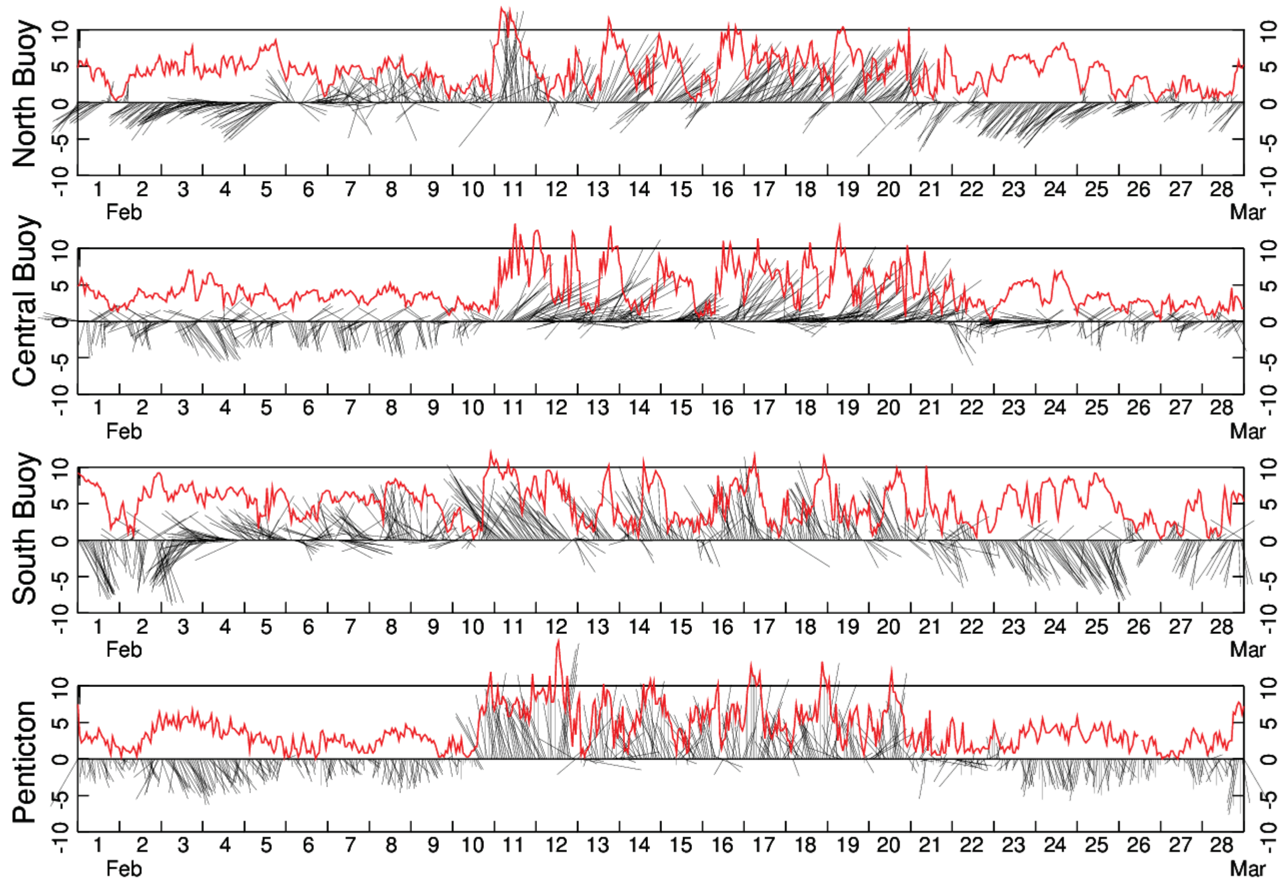


Figure 4-6 Wind stick plots (direction, date-time, and magnitude) from the 3 buoy stations (Spence and Hedstrom, 2015) and Penticton over the 2014 peak event.

4.3 Simulation of Waves on Lakeshores

NHC developed wave models in-house for each of Okanagan, Wood-Kalamalka, Skaha, Vaseux and Osoyoos lakes to simulate wave generation and propagation on the lakes. The SWAN model (Simulating Waves Nearshore or SWAN, version 41.20) has been used which incorporates physical processes such as wave generation by wind, wave propagation, white-capping, shoaling, wave breaking, bottom friction, sub-sea obstacles, wave setup and wave-wave interactions in its computations (Booij, N. et al., 2004).

A separate model grid for each lake was used with model grid resolutions of 50 m for Okanagan lake and 25 m for all other lakes. The model's bathymetric grids were generated from a digital elevation model (DEM) that includes a combination of BC Ministry of Environment (MOE) Fish and Wildlife Service (BC Ministry of Environment, 2019) and Canadian Hydrographic Charts (see section 5.2 for details).

The 200-year ARI wind events for each design direction (northerly and southerly) were used to force the SWAN model. For each event, a spatially varying wind field was developed and applied to both the coarse and fine grid models. The results of the SWAN simulation can be seen in Figure 4-7.

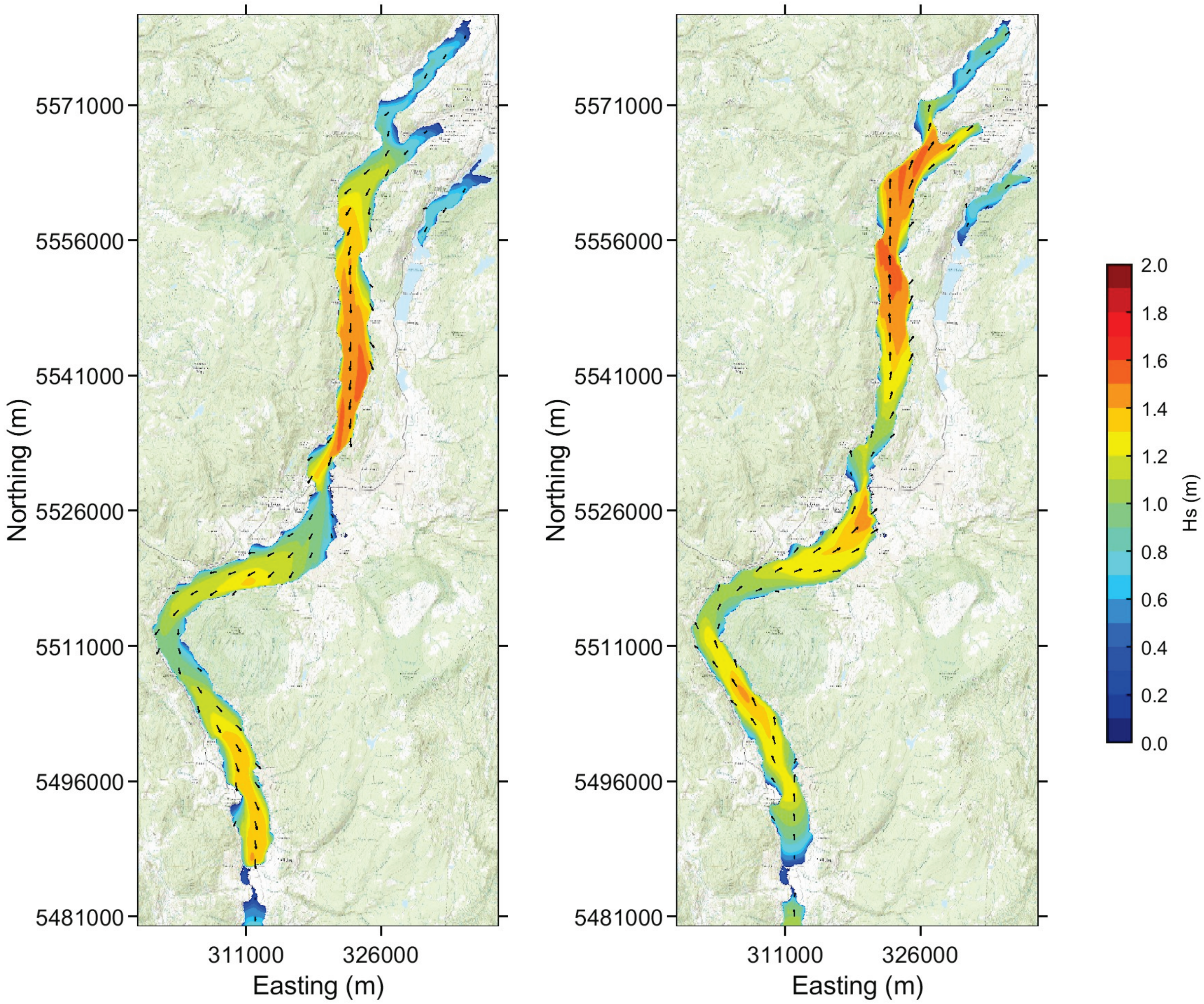


Figure 4-7 SWAN significant wave height results for Okanagan Lake for northerly (left) and southerly (right) design wind storms.

4.3.1 Analysis of Wave Effects

As waves approach the shoreline they steepen as they reach shallower water and eventually break as the water depth becomes too shallow for the wave height. The breaking waves can continue to runup the slope, limited by ground slope, roughness, and porosity. In addition, spray from the waves, particularly from the breaking waves, can splash or be blown shoreward. The limits on wave runup at the shoreline determines the extent and elevation over which waves act. Wave runup is therefore an important parameter to determine flood inundation extents from storms. Following the provincial guidelines (BC MoE, 2011), the two percent wave runup ($R_{2\%}$), which is the runup that only two percent of the wave runup values observed will reach or exceed, associated with the design storm event, is used to assess the wave effect.

The wave runup for each section was estimated using either the method described in European Overtopping Manual (EurOtop, 2018) or the method described in the USACE- Coastal Engineering Manual (CEM) (US Army Corps of Engineers, 2002). The CEM method is specifically for beaches with shallower slopes (<12%). The results are shown in Table 4-7; the values were applied to determine the FCL values for the design event on the shorelines. It is assumed in this analysis that the future foreshore slope and beach materials will be the same as that of the existing foreshore, and changes to the foreshore slopes would change the FCL.

Table 4-7 Wave effects estimated for study area for each wave effects zone.

Lake	Zone	Wave Properties			Shoreline Properties		Effect
		Significant Wave Height (Hs) (m)	Mean Wave Period (Tm) (sec)	Peak Wave Period (Tp) (sec)	Depth at the Toe (m)	Slope	R2% Wave Runup (m)
Okanagan	Zone 1	1.2	3.0	4.1	1.9	15%	1.4
Okanagan	Zone 2	1.1	3.1	4.1	2.1	40%	2.1
Okanagan	Zone 3	1.1	3.0	4.1	2.2	10%	0.9
Okanagan	Zone 4, 6, 8	1.6	3.8	5.1	2.3	40%	2.7
Okanagan	Zone 5	1.3	3.4	4.6	2.1	30%	1.8
Okanagan	Zone 7	1.3	3.4	4.6	1.9	25%	1.5
Kalamalka Lake	Zone 1	0.8	2.6	3.6	1.5	20%	0.8
Wood	Zone 1	0.9	2.5	3.3	1.4	10%	0.9
Wood	Zone 2	0.9	2.5	3.3	1.4	60%	1.9
Ellison	Zone 1	0.8	2.4	2.7	1.3	20%	1.0
Skaha Lake	Zone 1	1.0	2.9	3.7	2.0	30%	1.5
Skaha Lake	Zone 2	0.9	2.7	3.7	2.0	30%	1.2
Skaha Lake	Zone 3	0.7	2.4	3.7	1.0	5%	0.6
Skaha Lake	Zone 4	0.9	2.8	4.1	1.2	25%	0.9
Vaseux	Zone 1	0.6	2.0	2.6	1.3	10%	0.7
Osoyoos	Zone 1	0.7	2.4	3.3	2.4	20%	0.8

It is important to note that wave runup is largely governed by the geometry of the shoreline. A gentle sloping shoreline with vegetation will experience much lower levels of wave runup than a seawall for example. This is graphically shown in the photo below taken along the West Vancouver waterfront during a moderate storm occurring at an extremely high tide. The gentle shoreline where the photographer is standing is experiencing minor wave runup whereas the seawalls are experience wave runup in excess of 2m elevation.

Figure 4-8 Photo of wave runup in West Vancouver (credit: NHC).

It is noted that wave effects are limited to the area immediately adjacent to the shoreline and that for areas that are relatively flat the wave runup effect does not extend large distances inland as waves break near the shoreline and propagate landward as spilling waves that are reduced in height by interactions with vegetation, structures, and such. Thus, a shoreline FCL that includes wave effect is not necessarily an appropriate FCL for properties at similar elevations that are 40 m or more setback from the shoreline where large waves are breaking. In those cases, the depth of flooding is governed by the lake inundation, volume of wave overtopping, and the site drainage.

4.4 Potential for Tsunami-Driven Waves

4.4.1 Overview

In addition to wave and storm events, high water and shoreline inundation could potentially occur from a tsunami event resulting in localized flooding and property damage. Previously denoted as tidal waves, the Japanese term tsunami is now used to denote long period waves (5 to 60 minutes) that radiate out from the rapid displacement of a large volume of water. The displacement is triggered by a large impulse of energy and, as such, can result from a wide variety of sources such as: earthquakes, landslides, volcanic eruptions, glacier calving events, or impacts from a meteorite. Major tsunami events generally are a result of earthquakes that produce substantial vertical movement of the sea floor in sufficiently shallow water. This requirement is why a substantial portion of the most notable tsunamis occur in the active tectonic margin surrounding the Pacific Ocean (e.g. 1700 Japan, 1963 Alaska, 2004 India, and 2011 Japan).

While earthquakes are the source for more than 80% of all documented tsunami events, landslides constitute the second-most important cause of tsunamis (Løvholt et al., 2015). Despite the comparatively low risk for landslides in the Okanagan Valley relative to Coastal BC, the combination of steep bedrock slopes and poorly consolidated silt bluffs make landslides the leading reported geological hazard in the region (AE, 2017). Were a landslide to enter one of the lakes, it could potentially generate a Tsunami. This section evaluates the history of landslides and landslide-generated waves around

Okanagan Lake and potential triggers for future tsunami waves based on the geologic setting and seismic risk in the valley.

4.4.2 Landslide Induced

While terrestrial tsunamis are rarer than their oceanic counterparts, subaerial landslides in waterbodies can produce devasting waves that have claimed the lives of thousands around the world (Løvholt et al., 2015). These typically occur in mountain lake basins and reservoirs where landslides are triggered on slopes due to earthquakes, poor drainage, and over-steepening. Recovery of a landscape in response to deglaciation may also contribute to the mass failure of material; collapse of the Taan Fiord valley cause a tsunami to form in 2015 (Higman et al., 2018). Lake tsunamis have the potential to be more damaging than those on the coast because lakes are closed systems. The maximum height of the wave can be substantially higher than that possible at the coast because of basin constraint, for example the Mt. St. Helens -caused Spirit Lake tsunami reached 260 m (Voight et al., 1983). In addition, instead of a single series of waves, lake tsunamis can generate seiches, standing waves that can oscillate in the enclosed water body for hours (Ichinose et al., 2000).

Perhaps the best local example is the December 2007 Chehalis Lake tsunami, where a 3 million cubic meter rockslide entered the north end of the lake and generated a tsunami with local runup exceeding 35 meters. While the entire 8.5 km-long shoreline was altered, the tsunami had the greatest impact on low-gradient shores and those areas closest to the slide (NHC, 2008a; Roberts et al., 2013). In 1959 an earthquake triggered a seiche in Hebgen Lake, where oscillating waves propagated for hours overtopped the dam. Other international examples include the 2003 Three Gorges Reservoir Gongjiafang landslide and river tsunami that claimed the lives of 14 people from the 20-m wave, and the 1963 landslide generated tsunami in the Vajont Dam reservoir in Italy, where a wave overtopped the dam and killed over 2000 people downstream (Dai et al., 2004; Wolter et al., 2016).

Only two cases of landslide-generated tsunami waves in Okanagan Lake have been documented (Table 4-8; Tannant, 2011) with wave heights ranging from 1.5 to 4 meters. The tsunami wave overtopped a home in the 1951 event, fortunately without any casualties. While sliding mass volumes have not been well-documented, the 2008 Goat Bluff landslide suggests that tsunami-triggering large slides and rockfalls along the lake perimeter are possible. The Goat Bluff slide occurred during construction of Highway 97 road widening along a steep roadcut between Peachland and Summerland. Excavation at the toe activated a tensile fracture upslope, producing a 150,000 m^3 sliding mass capable of dropping into the lake (Bean and Oldrich, 2011). The potential mass movements, and subsequent tsunami hazard, were avoided through unloading and stabilizing the at-risk slope.

Table 4-8 Notable landslides along the Okanagan Lake margin.

Date	Location	Wave Height (meters)	Description
8/3/1942	Across Lake from Summerland (exact location unknown)	1.5	3 waves traveled across lake to Summerland causing damage to docks, piers and cabins
7/20/1951	Poplar Grove	4	Tsunami wave washed over a house along the shoreline
8/20/1969	Old Agricultural Research Station	-	Consecutive slides in Dec 1971 and 1974
3/14/1975	Lake Okanagan Provincial Park	-	Activated on access road on silt bluff
9/15/1992	Summerland	-	Silt bluff slide travelled across road burying shoreline garage in 5 m of silt
10/23/2008	Goat Bluff (Hwy 97 between Summerland and Peachland)	-	150,000 m^3 sliding mass pre-emptively unloaded to prevent full slide and tsunami wave

The nature of landslide-triggered tsunami waves has been studied in physical laboratories and through geomorphic evidence. (McFall and Fritz, 2016) analyzed the effects of the lateral hill slope curvature and landslide granulometry on the offshore wave characteristics of tsunamis using a physical model of gravel and cobble slide sources. Results suggest that bulkier materials produce larger wave amplitudes and that, on average, the leading wave crest is larger when generated on a planar rather than convex conical hillslope. This presents a complicated implication for Okanagan Lake, where the main slide material is fine granular silt and sand and the sliding surfaces planar, as these two features will act against each other. Although a landslide of glaciolacustrine silts may not trigger as large of a wave as sliding bedrock, the total destructive force of a wave depends not only on granularity and slope, but also on landslide impact velocity, acceleration, and the total displacement volume and frontal area (Løvholt et al., 2015). In the event of retrogressive slides[1] with multi-staged release, the prolonged period of material input further complicates wave behavior prediction.

4.4.3 Regional Geology and Seismicity

Okanagan Lake is the remnant of ancestral Lake Penticton, a large glacial lake from the most recent Fraser Glaciation. The tall and steep silt bluffs and erosional scarps that border the lake are a product of numerous punctuated lowering of the ancient lake. Landslides in silt and sand glaciolacustrine sediment are well-documented in the literature (e.g. Desloges and Gilbert, 1994; Marko et al., 2010). Cited landslide triggers in the region include improper drainage from upslope agricultural lands, natural elevated water levels, and oversteepening of slopes. There are no known recorded events of

[1] In a retrogressive landslide the rupture surface is extending in the direction opposite to the movement of the displaced material, http://www.ukgeohazards.info/pages/eng_geol/landslide_geohazard/eng_geol_landslides_classification.htm, accessed 31 March 2020.

earthquake-triggered landslides in the valley, yet small earthquakes are frequent and may potentially provide the trigger for at-risk slopes. The north-south striking Okanagan Valley Normal Fault runs through Okanagan Lake down the center of the valley into Skaha Lake, resulting in contrasting bedrock lithologies below the valley fill of glaciolacustrine silts and glacial till. The fault separates metamorphic and plutonic bedrock on the eastern foot wall with volcanic, plutonic, and less competent sedimentary rocks on the western hanging wall. In various locations, particularly Summerland, this tertiary claystone provides for a weak failure plane in which multiple landslides have and continue to occur. Summerland's 'Perpetual Landslide' is perhaps the best example of this (Riglin, 1977). The Valley-striking fault has been inactive for 20 million years, putting the fault at low risk of rupturing (Roed and Fulton, 2019).

According to the 2015 National Building Code of Canada the Okanagan Valley falls within a low seismic risk zone. The threat of severe shaking from a large earthquake is therefore low in the tectonically inactive valley. Small earthquakes are common, with Penticton experiencing around 12 quakes per year between Magnitude 2 to 4 (See Figure X; Natural Resources Canada, 2020), however, discussion on the tectonic triggers of these quakes is missing from the literature. A likely cause of these frequent yet small quakes is stress transfer from the convergence of the North American and Pacific Plates, with energy traveling hundreds of kilometers through the crust to reactive small faults (Steacy, 2005; Stein, 2003). Despite the near location of quakes in the valley, distant large quakes in Washington and Coastal BC have caused the most damage to the Okanagan Valley in the recorded past.

Estimating the risk of an earthquake-triggered landslide capable of producing tsunami waves in Okanagan Lake is challenging given the lack of cited earthquake-triggered slides in the valley. Solely based on the likelihood of earthquakes large enough to cause failures on their own, the risk appears to be very low. Risk, however, increases when the possibility of seismic activity coincides with areas of instability; those with Factors of Safety approaching 1. Given the record of terrain instabilities along the lake margin and the probability of distal large quakes near the coast, the threat is still present. Specifically, in the Okanagan Valley, this would likely occur when slopes experience peak seepage discharge and pore pressure is at a maximum, minimizing resistive stresses. Ongoing proactive measures including transitioning to drip irrigation and development restrictions reduce this risk, but do not preclude it (AE, 2017a).

4.5 Conclusions, Recommendations, and Future Work

Generalized wave effects have been calculated for zones with similar terrain along each lake. This value should be added to the lake FCL for near shore locations. While the winds varying across the valley, Penticton was a suitable choice for the seasonal design storm combined with a synthetic spatially-varying wind field. These inputs were used to drive the wave modelling and provide input for the wave effects analysis which informs the flood mapping and FCL development. The wave results are limited by the accuracy of all data used in the modelling. The bathymetry available for several of the lakes is particularly coarse and bathymetric surveys (particularly in the nearshore) could improve the accuracy of the nearshore wave results.

It is recommended that any major developments or any change to the existing shoreline profiles require a site-specific analysis to determine a new appropriate wave runup and a new FCL. Residents or developers could also complete specific flood hazard assessments to refine the FCL for their specific location if they so chose. It is recommended that site specific hazard assessment or design include refinement of wave effects based on local bathymetry, and shoreline slope, roughness, and porosity.

For future work, improvements to the bathymetric data for all the lakes should be considered with a focus on the nearshore. This could be used to improve wave results and improve site specific analysis.

Landslide generated tsunamis have been documented in Okanagan Lake over the last 80 years and can result in runup in excess of that calculated for the wind generated wave events. More detailed study of potential landslide zones, the generation and propagation of tsunamis, and subsequent runup zones should be conducted and added to the floodplain maps. Further work is recommended in assessing tsunami hazard in the Okanagan Valley overall, and that this be provided at minimum as information on floodplain maps or included in FCLs where relevant.