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Regional Wave Run-Up Study for the Province of New Brunswick

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Executive Summary

The National Research Council's Ocean, Coastal and River Engineering (NRC-OCRE) Research Centre was appointed by the New Brunswick Department of Environment and Local Government (NBDELG) to conduct a regional wave run-up study for the province of New Brunswick. The study was required to inform the development of coastal flood hazard maps for approximately 2,270 linear kilometers of the province's coast.

Previous studies of nearshore extreme water levels funded by NBDELG, which established extreme water levels for 14 coastal flood hazard zones in New Brunswick, did not include allowances for wave-related contributions to coastal flood hazards such as wave run-up on the shore. The regional wave run-up study is the first step towards addressing this data gap, by providing representative estimates of extreme wave run-up heights in 614 sub-zones along the New Brunswick coast.

The regional wave run-up study involved four principal tasks (or phases), summarized as follows:

Phase 1 – Offshore extreme wind and waves analysis
A long-term (61-year) hindcast database of wind and wave conditions was statistically analyzed to determine extreme offshore wind and wave parameters (such as wave heights, wave periods, directions) corresponding to 1 year and 100 year return periods.

Phase 2 – Regional wave transformation modelling
A series of nested numerical wave models were developed, calibrated and validated, and used to transform the offshore extreme wave conditions determined in Phase 1 to the New Brunswick nearshore, and to evaluate nearshore extreme wave conditions generated by winds blowing over local fetches in the Gulf of Saint Lawrence and Bay of Fundy.

Phase 3 – Wave run-up calculations
Empirical wave run-up formulae were used to calculate representative wave run-up heights in 614 sub-zones, identified and classified according to extreme water level characteristics, wave exposure, shore type and gradient/slope.

Phase 4 – Data visualization tool support
A review of options for web-based data visualization and mapping of the study output was carried out to provide suggestions to NBDELG on how to effectively disseminate coastal flood hazard mapping information to public users. The review also informed the formatting of data deliverables generated by the regional wave run-up study, for incorporation in NDELG's web-based visualization tool.

The primary outputs from the study consisted of:

- Gridded nearshore extreme wave conditions (maximum significant wave heights and associated peak wave periods) corresponding to 1 year and 100 year return period offshore wind/wave conditions in combination with 2100 extreme water levels;
- Representative wave run-up heights (corresponding to 2% wave run-up heights above still water levels) in 614 sub-zones, corresponding to the same events/return periods described above; and

- Suggested explanatory (summary) text for incorporation in NBDELG's data visualization tool.

The outputs were provided in GIS-compatible formats, determined based on the Phase 4 review. Recommendations from the review included a continued focus on the development and enhancement of NBDELG's existing ArcGIS Online-based web mapping application.

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1 Introduction

The New Brunswick Department of Environment and Local Government's (NBDELG) Coastal Flood Hazard Mapping project is an ongoing initiative to create new flood hazard maps for approximately 2,270 linear kilometers of the province's coast. The National Research Council's Ocean, Coastal and River Engineering (NRC-OCRE) Research Centre was appointed by NBDELG to conduct a regional wave run-up study, to develop regional estimates of nearshore extreme (storm) waves and associated wave run-up for 14 identified coastal flood hazard zones. The output from the study is intended to inform NBDELG's coastal flood hazard mapping and to support the development of a web-based data visualization tool for public dissemination.

This report presents the study methodology, results and data deliverables generated by the study.

1.1 Background

Coastal flooding events are a regular occurrence in New Brunswick, and it is anticipated that rising sea levels will lead to increases in the frequency and magnitude of coastal flooding in the future. In 2014, New Brunswick's Flood Risk Reduction Strategy [1] called for "initiating the renewal and expansion of New Brunswick's existing set of coastal and inland flood hazard maps", motivating the establishment of the Coastal Flood Hazard Mapping project.

Extreme sea level predictions were previously developed for some parts of the New Brunswick coast [2]. However, a complete set of coastal flood hazard maps based on a unified mapping methodology and assumptions does not yet exist. The Coastal Flood Hazard Mapping project aims to address this gap. Once mapping is completed, the maps will be made freely available on a web-based platform.

Under the Coastal Flood Hazard Mapping project, the province has funded studies to evaluate future extreme sea levels [3]. The extreme sea level estimates included allowances for:

- Tides;
- Extreme storm surges (atmospheric pressure setup and wind setup); and
- Projected relative sea level rise incorporating estimates of future global sea levels and regional adjustments (e.g. for crustal subsidence).

The extreme water levels were evaluated for a set of 14 coastal flood hazard zones throughout New Brunswick, classified according to tide and storm surge characteristics (Figure 1). Wave-related contributions to the total extreme water levels (such as wave run-up) were not considered, nor were coastal erosion, or riverine contributions to coastal flooding in estuarine areas. Of these contributions, wave run-up was identified by NBDELG as an immediate priority and is the primary focus of this report.

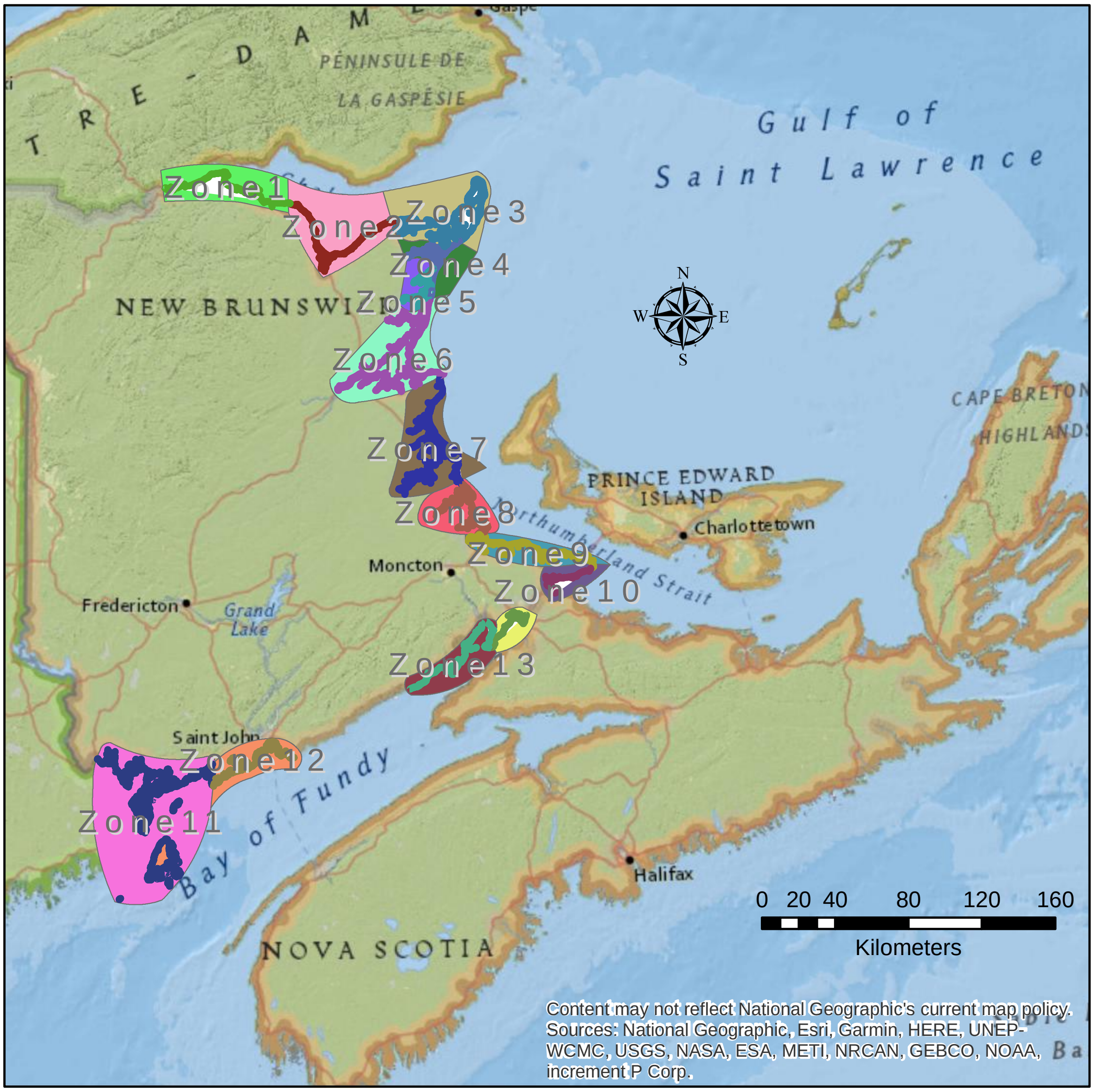

Figure 1. Coastal flood hazard zones in the province of New Brunswick.

1.2 Motivation

Coastal flooding often occurs during extreme (storm) events resulting in elevated water levels at the shore. There are a number of potential factors contributing to an extreme water level event that may act in combination to cause coastal flooding (Figure 2), including tides, storm surges, sea level rise, and wave effects. The combined effects of tides, storm surges and sea level rise on extreme water levels have previously been evaluated for the New Brunswick coast [3]. Wave run-up is the vertical height of wave uprush on the shore above the still water level. Wave uprush consists of two components:

- Wave set-up – an increase in mean water level due to wave action and breaking that fluctuates slowly with changes in storm wave conditions; and
- Wave swash – short-term fluctuations in water level about the elevation of wave set-up on time scales similar to the period of incident waves.

The primary motivation for the study described herein is the need to evaluate wave run-up contributions to extreme water levels on the New Brunswick coast, to inform coastal flood hazard assessment and mapping.

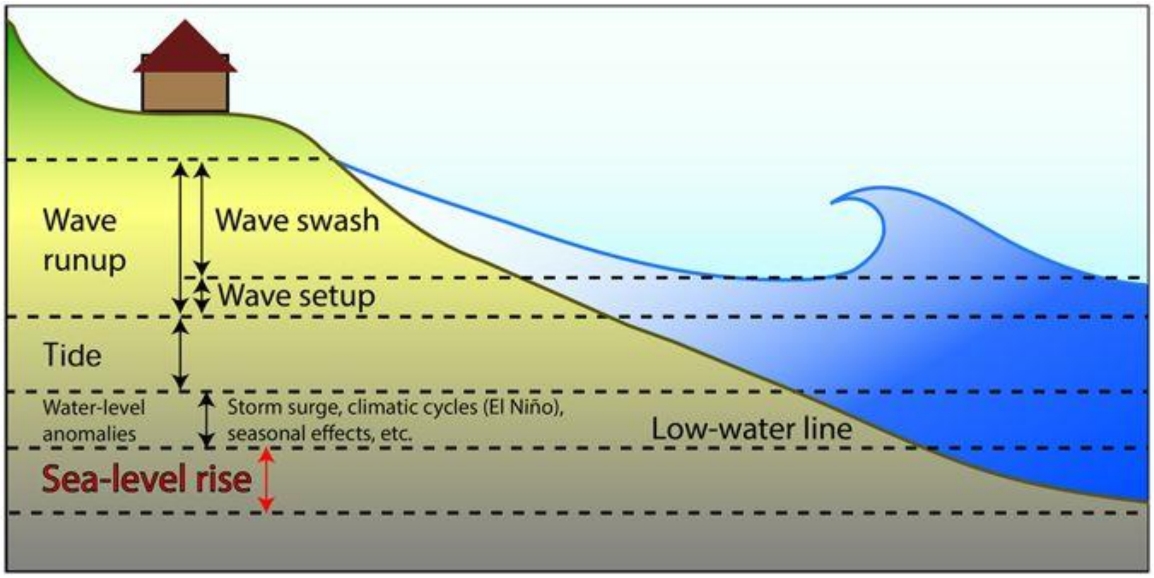

Figure 2. Water level and wave contributions to coastal flood hazards. Source: [4]

1.3 Scope and Objectives

The main objective of the study is to develop regional estimates of nearshore extreme wave conditions and wave run-up heights associated with extreme (storm) conditions for the 14 identified coastal flood hazard zones.

1.4 Overview of Study Methodology

The regional wave run-up study methodology involved four distinct phases:

- Phase 1 – Offshore extreme wind and waves analysis (described in Section 2);
- Phase 2 – Regional wave transformation modelling (Section 3);
- Phase 3 – Wave run-up calculations (Section 4); and
- Phase 4 – Data visualization tool support (Section 5).

The Phase 1 analysis determined offshore extreme wave conditions in the Gulf of Saint Lawrence and outside the Bay of Fundy, which were transformed to the New Brunswick nearshore in Phase 2 using numerical modelling techniques. The nearshore extreme wave conditions evaluated in Phase 2 provided the basis for evaluating wave run-up on the New Brunswick shore in Phase 3. Phase 4 involved a technical review and advice to NBDELG on options for communicating coastal flood hazard information to the public.

1.5 Definitions

The following definitions are provided to explain key technical terms used in this report:

2% wave run-up limit, $R_{u2\%}$	The elevation limit of *wave run-up* exceeded by 2% of the waves arriving at the shore in a given storm or *sea state*.
Fetch	The distance over which wind blows to generate waves.

Mean sea level	The sea level averaged over a long period of time (e.g. 19 years).
Peak wave direction, θ_p	The direction of propagation associated with the highest energy waves in a *sea state*.
Peak wave period, T_p	The wave period associated with the highest energy waves in a *sea state*.
Relative sea level rise	Relative sea level rise is a positive change in sea level relative to the land. Relative sea level changes can be caused by absolute changes in sea level (e.g. due to melting of glaciers) and/or by land movement (e.g. crustal uplift or subsidence). Sea levels can also fall relative to land.
Sea state	The properties of irregular sea waves at a given time and place, which may be described in terms of a *wave spectrum*, or more simply in terms of key parameters such as statistical measures of *wave height* (e.g. *significant wave height*) and *period* (e.g. *peak wave period*).
Significant wave height, $H_s = H_{1/3}$	The average of the highest third of waves in a *sea state*.
Spectral significant wave height, H_{m0}	A representative *wave height* determined from the *wave spectrum* based on $4\sqrt{m_0}$, where m_0 is the integral of the power spectrum. In deep water, this parameter is very similar to the *significant wave height*, H_s, and the terms are used interchangeably in this report.
Spreading (angular or directional)	A measure of the range of directions in which waves in a *sea state* propagate. *Swell sea* tends to be have a focused, narrow directional range, whereas *wind sea* may include waves propagating in a wide range of directions.
Storm surge	The combined contribution of meteorological (wind and atmospheric pressure) effects to the *still water level*.
Still water level	The average water surface elevation excluding short-term or local variations due to waves but including the effects of *tides*, *storm surges*, seiches, seasonal or climate variability effects, and *mean sea level* (including *relative sea level rise*).
Swell sea	The low *frequency* (long *period*) component of a *sea state* (i.e. long period waves propagating to a given site from distant oceanic storms)
Tides	Cyclical, largely predictable, fluctuations in sea levels caused primarily by the gravitational attraction of the moon and the sun.
Wave frequency	The inverse of *wave period*.
Wave height	The difference between the crest (point of maximum elevation) and trough (point of minimum elevation) elevations of a passing wave
Wave hindcast	Prediction of historical wave conditions). Contrasts with “forecast”, which is a prediction of future conditions.
Wave period	The elapsed time between the passage of two wave crests (or troughs) past a fixed point.
Wave run-up	The vertical height of wave uprush on the shore above

	the still water level.
Wave spectrum	A mathematical description of *sea state* conditions, e.g. defining the distribution of wave energy amongst different *frequencies* / *periods.*
Wind sea	The high *frequency* (short *period*) component of a *sea state* (i.e. short period waves generated by winds blowing over local fetches).

2 Offshore Wind and Waves

The following sub-sections describe Phase 1 of the study (offshore wind and wave analysis). The primary objectives of the analysis are to gain insight to the temporal and spatial variability of extreme wind and wave conditions offshore of New Brunswick, and to establish extreme offshore wind and wave parameters for input to numerical wave models (in Phase 2).

2.1 Hindcast Data

Offshore wind and wave time series data based on the Meteorological Service of Canada and Oceanweather hindcast models (MSC50) [5] [6] was obtained from the Department of Fisheries and Oceans Canada. The MSC50 hindcast dataset provides time series data at hourly intervals for 21 wind and wave parameters, derived from a reanalysis of historical surface winds and ocean surface waves off the Canadian East Coast for the period 1954-2015 (62 years). The dataset covers much of the waters off the coast of the Canadian Maritimes and provides wind and wave parameters on a 0.1-degree resolution grid domain (18551 points). Two-dimensional (frequency and directions) hindcast wave spectra are provided at selected locations.

The MSC50 grid points near the New Brunswick coast are shown in Figure 1. Definitions of the 12 key wind and wave parameters that were selected for analysis as part of this study are provided in Table 1 and Table 2. These parameters were chosen to provide prerequisite input to the numerical wave modelling (in Phase 2 of the study). In addition to total sea state parameters (significant wave heights, peak wave periods and peak wave directions), parameters for the primary and secondary partitions of the wave spectra are provided. The primary and secondary partitions refer to wind sea and swell sea components of the wave spectrum, respectively. Wind sea is the high frequency component of a sea state (i.e. short period waves generated by winds blowing over local fetches) and swell sea is the low frequency (long period) component.

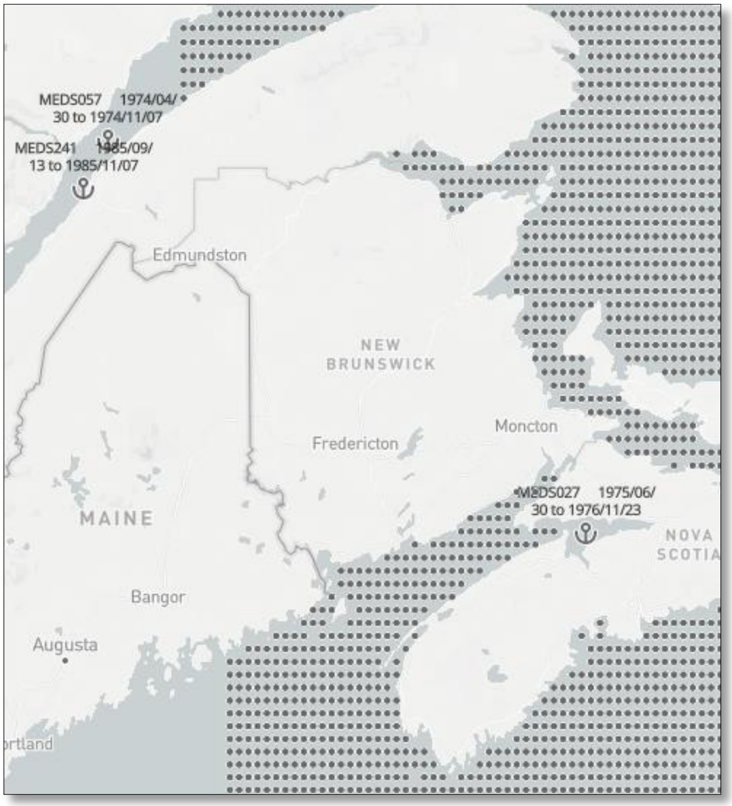

Figure 3: MSC50 grid points (black dots) near the New Brunswick coast.

Table 1: Definitions of wave parameters in the MSC50 database.

Parameter	Unit	Definition
H_s	m	***Significant Wave Height*** $= 4\sqrt{E}$, where E is the energy of the total spectrum
T_p	s	***Peak Period*** defined as the inverse of the most energetic frequency of the total spectrum
Dir	$^{o}/North$	***Peak Direction*** to which waves are traveling, clockwise from north
H_{s_sea}	m	***Significant Wave Height for Wind-Sea*** $4\sqrt{ETTSEA}$, where $ETTSEA$ is the energy of the total variance of primary partition “sea”
T_{p_sea}	s	***Peak Period for Wind-Sea*** peak spectral period of primary partition
Dir_{sea}	$^{o}/North$	***Peak Direction for Wind-Sea*** vector mean direction of primary partition to which waves are traveling, clockwise from north

H_{s_swell}	m	***Significant Wave Height for Swell-Sea*** $4\sqrt{ETTSW}$, where $ETTSW$ is the energy of the total variance of secondary partition "swell"
T_{p_swell}	s	***Peak Period for Swell-Sea*** peak spectral period of secondary partition to which waves are traveling, clockwise from north
Dir_{swell}	$°/\,North$	***Peak Direction for Swell-Sea*** vector mean direction of secondary partition to which waves are traveling, clockwise from north
$ANGSPR$	$°/\,North$	***Angular Spreading Function*** *related to* $\cos\theta^n$ *spreading as* $n = \frac{2 * ANGSPR * \pi/180}{1 - ANGSPR * \pi/180}$

Table 2: Definitions of wind parameters in the MSC50 database.

Parameter	Unit	Definition
W_s	m/s	***Wind Speed*** 1-hour average of the effective neutral wind at a height of 10 meters
W_d	$°/\,North$	***Wind Direction*** From which the wind is blowing, clockwise from true north (meteorological convention)

2.2 Wave Buoy Data and Validation

Measured wave buoy data was obtained from Department of Fisheries and Oceans Canada archives (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/waves-vagues/index-eng.htm). Wave buoy data was used to validate the offshore hindcast data (MSC50) for use as input to the numerical wave modelling (in Phase 2).

MSC50 hindcast data was compared to measured wave buoy data at two locations:

- Southern Region (Gulf of Maine) – using data from wave buoy ID 44131 and MSC50 grid location M6006973.
- Northern Region (Gulf of Saint Lawrence) – using data from wave buoy ID 44153 and MSC50 grid location M6012283.

Figure 4 and Figure 5 show measured (red dots) and hindcast (black line) wind and wave parameters (significant wave height, peak period, peak direction, wind speed and wind direction) for a month of measurements. The comparisons show general agreement between the hindcast data and measurements for a range of wind and wave conditions, giving confidence in the hindcast data for use as input to the numerical wave modelling.

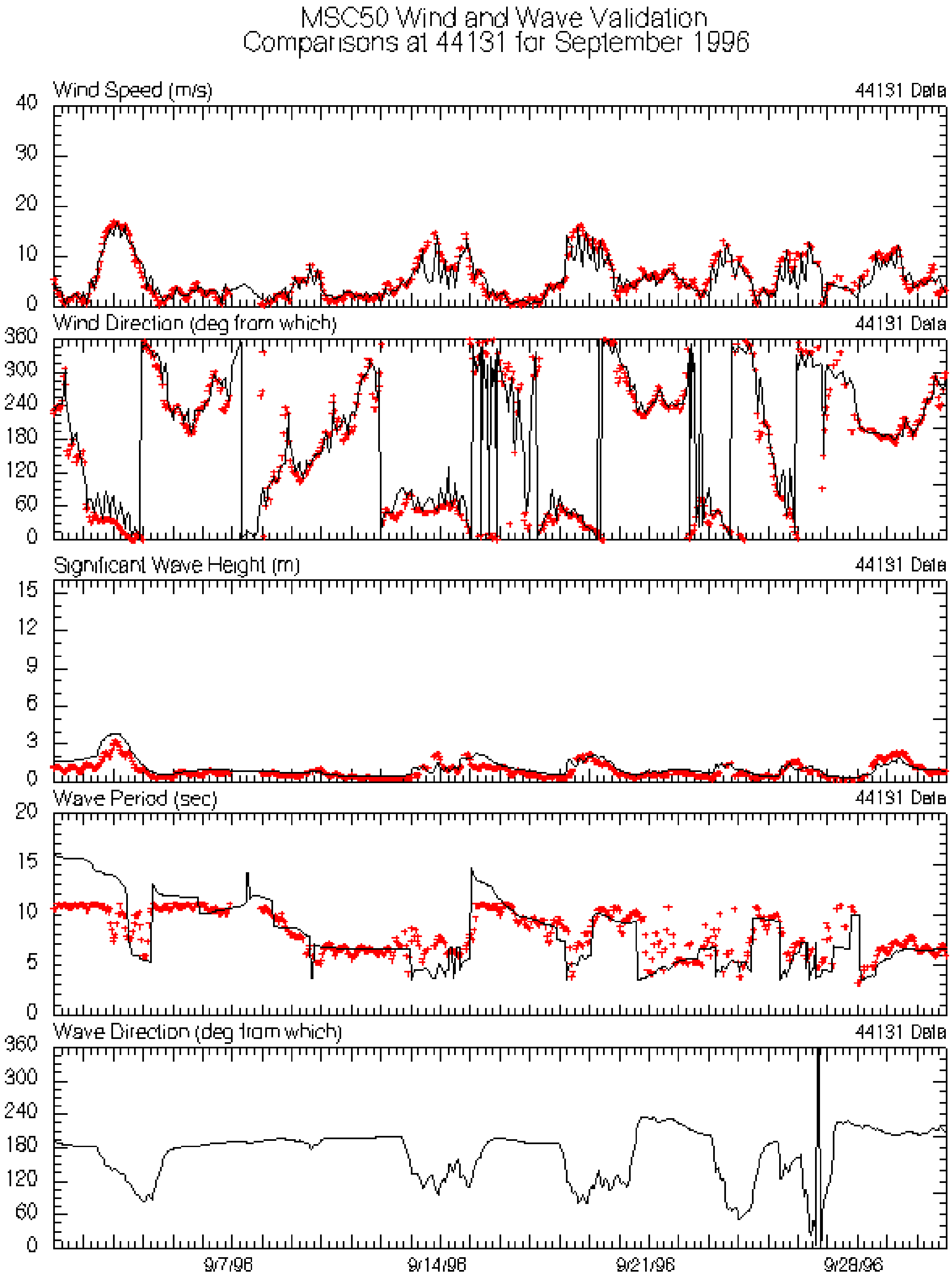

Figure 4 : MSC50 Wind and Wave Validation in the Southern Region / Gulf of Maine (black line=MSC50, red dots=Measured Wave Buoy Data)

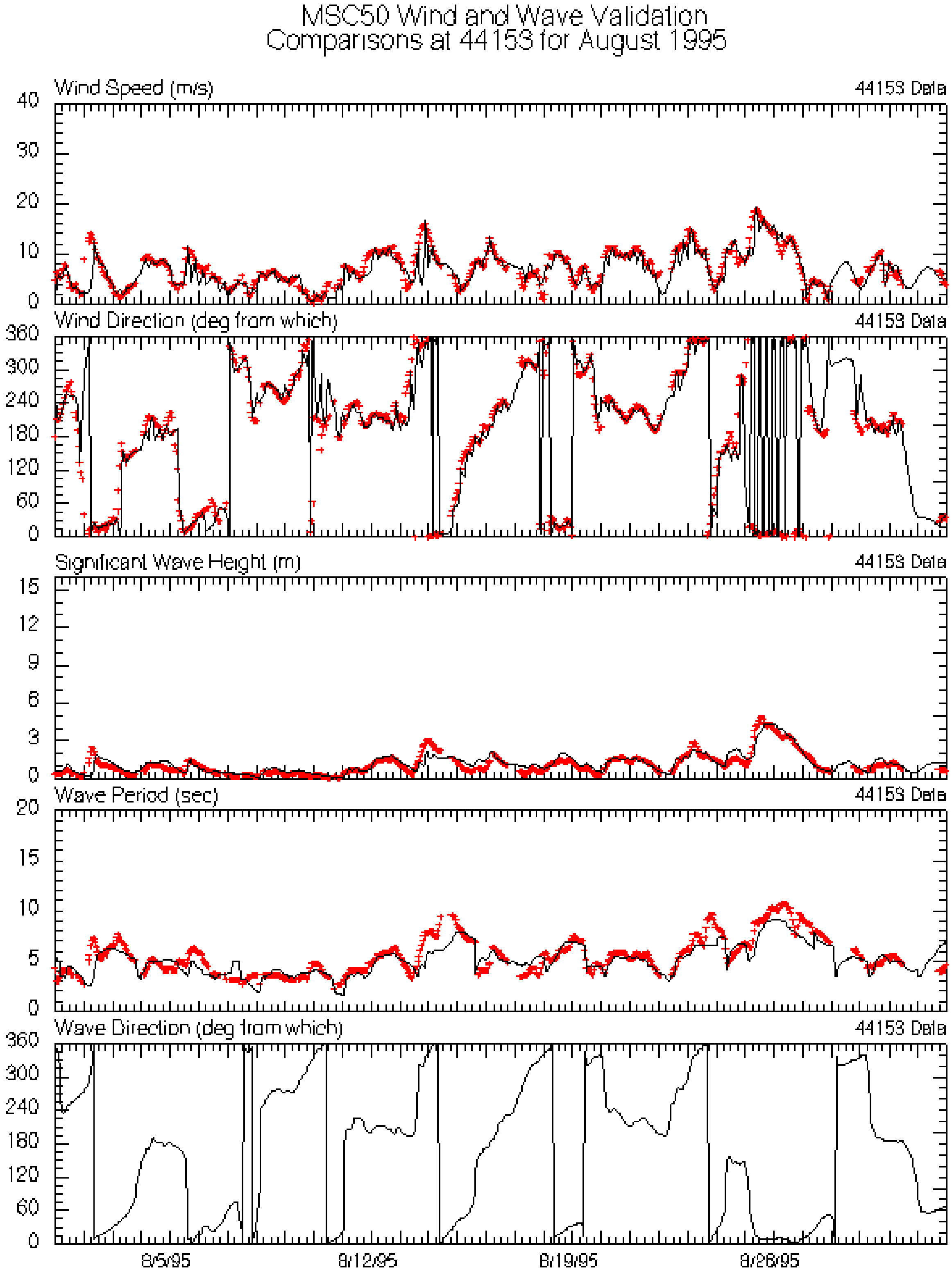

Figure 5 : MSC50 Wind and Wave Validation on the Northern Region / Gulf of Saint Lawrence (black line=MSC50, red dots=Measured Wave Buoy Data)

2.3 Methodology

The approach to the offshore wind and wave analysis involved the following sequence of steps:

1. Data preparation and homogenization:
    - Wave and wind time-series data were extracted from the MSC50 dataset at selected grid points near the offshore boundary of the numerical wave models being developed in Phase 2;
    - The data was sorted and analyzed to identify samples of independent storms within common parent statistical distributions, determined based on wave/wind directions (rose analysis), storm types, distribution of swell (low frequency waves propagating from the deep ocean) and wind sea (short frequency waves generated by winds blowing over local fetches), fetch lengths and directions.
2. Statistical analysis:
    - Extreme value analyses (frequency analyses) were performed using the storm peak significant wave heights and wind speeds to evaluate return values associated with a range of return periods.
3. Evaluation of spectral wave parameters:
    - Spectral wave parameters (peak wave periods, angular/directional spreading, spectral peakedness) associated with the return values of significant wave height were assessed through regression.

Further details on each of these steps are provided in the following sections.

2.3.1 Data Preparation and Homogenization

The working numerical wave transformation model domains (Section 3) were overlaid with the MSC50 grid points to assist in identifying appropriate grid points to use for input to the wave transformation modelling in Phase 2. MSC50 grid points close to the model boundaries were selected for analysis based on their distances relative to the shore, long fetch distances, and dominant wave and wind direction. Time series wind and wave data was extracted from the MSC50 database for the selected points.

A prerequisite for conducting extreme value (statistical) analysis of wind or wave data is to identify independent events (storms) within the time series. For example, two peaks in significant wave heights occurring within a short timeframe may be part of the same storm and would therefore be correlated (i.e. not independent). Individual storms were therefore identified by specifying a minimum threshold value of significant wave height or wind speed and a minimum inter-event duration. Another important prerequisite for conducting extreme value (statistical) analysis of wind or wave data is homogeneity [7]. Individual data in a common parent distribution must have a common parent distribution. For example, swell waves propagating towards the Bay of Fundy from tropical cyclone systems (i.e. hurricanes) would belong to a different statistical population to wind sea generated in local or regional waters (e.g. by Nor’easter storms). The time series was therefore sorted by directional sectors, wave periods, seasons (e.g. summer/winter) and storm system types (e.g. hurricanes) to identify independent storms (sea states and wind speeds) from common parent statistical distributions.

Wave/wind rose plots were generated from the 62-year time series to facilitate visual identification of the dominant storm wind and wave directional sectors and patterns. Rose plots provide a succinct view of magnitude (wind speed or wave height), frequency and direction at a particular location. The plots use a polar co-ordinate system of gridding to indicate direction. Colour bands are used to indicate magnitude, and the length of each colour band indicates the frequency or percentage occurrence (scales shown as concentric circles). All wave/wind roses were created using 16 sectors (i.e. 22.5 degree bins). Monthly roses were also created to illustrate seasonal variations in storm events (magnitude and direction).

Analysis of two-dimensional wave spectra for selected storm events revealed that the offshore sea states often consisted of bi-modal spectra with distinct swell (low frequency) and wind sea (high frequency) components, often propagating in different directions. Swell and wind sea components of the wave spectrum were therefore isolated and sorted for separate statistical analysis.

2.3.2 Statistical Analysis

Extreme value analyses of significant wave heights and wind speeds were carried out for the selected MSC50 grid points using the sorted, homogenized storm datasets and applying the Peak-Over-Threshold (POT) method [8]. The POT method uses peak values (of significant wave height or wind speed) exceeding a specified threshold to identify “extreme” events within a continuous record. The advantage of this approach (as opposed to the annual maxima method more commonly used in hydrologic analysis in Canada) is that it makes use of more data from records of limited length, as more than one value per year can be considered for the analysis. This can be an important advantage when analyzing offshore wind and wave datasets, as the requirement for homogeneity may limit the number of events available for each sample. In addition, due to inter-annual and inter-decadal climate variability effects, there may not necessarily be an example of every type of storm event in every year of the record.

In this study, storm peaks were defined as any event exceeding a specified minimum threshold and separated by at least 24 hours. A minimum of 50 peaks were required in order to compute the corresponding extremes (corresponding to a mean rate of extreme events of at least 0.8/year, similar to an annual maxima approach). Where possible, mean annual rates (λ_T) of approximately 2/year were targeted, consistent with recommendations of Mazas and Hamm [8], i.e.

$$\lambda_T = \frac{N_T}{K} \approx 2$$

where N_T is the number of peaks/events over a period of K years.

Peaks were determined separately for significant wave heights (H_s) and wind speeds (W_s), since wind and waves are not always locally correlated offshore. Spectral wave parameters (periods, directions, spectral peakedness and directional spreading) at the time of the peak H_s or peak W_s of each storm were identified.

A Generalized Pareto Distribution (GPD) fit to the storm peak data was performed using the Maximum Product of Spacings (MPS) estimator. The minimum threshold was adjusted to include approximately 2 storms per year on average, with an acceptable goodness-of-fit.

Peak significant wave height and wave speed were determined for return periods in the range 1 to 100 years. 95% confidence intervals for each return period were also calculated.

2.3.3 Spectral Wave Parameters

In addition to significant wave heights and wind speeds, the regional wave transformation models (Phase 2) require information on wave spectra to be specified at offshore boundaries. This includes information on the peak frequency of the wave spectrum (i.e. the inverse of the peak wave period), directional spreading (e.g. swell tends to be narrow-banded or uni-directional, whereas wind sea tends to propagate in a wider range of directions), and the distribution of wave energy in different frequencies (i.e. spectral peakedness).

The peak wave period and angular/directional spreading associated with return values of significant wave height were determined based on the correlation of these parameters with storm significant wave heights from scatter plots (e.g. Figure 6 and Figure 7). Where necessary (i.e. in cases of significant scatter in the data), values were manually selected based on visual inspection of the scatter plots.

The spectral peakedness parameter (which defines the bandwidth/narrowness of a standard JONSWAP parametric wave spectrum) was determined for each return period by adjusting the value to provide a good fit (visually assessed) between a JONSWAP spectrum and the peaks of several storm wave spectra with significant wave heights close to that of the return period being evaluated (e.g. Figure 8).

Two-dimensional (frequency and direction) wave energy spectra coinciding with the peaks of the storms were plotted to identify the directional distribution of different components of the sea states (e.g. locally generated wind sea or swell), as shown in Figure 9.

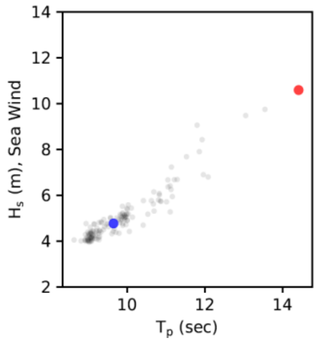

Figure 6 : Example of peak wave period and associated with return values of significant wave height (blue dot=1yr, red dot=100yr)

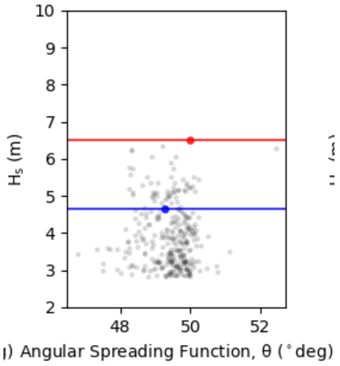

Figure 7 : Example angular/directional spreading associated with return values of significant wave height (blue dot=1yr, red dot=100yr)

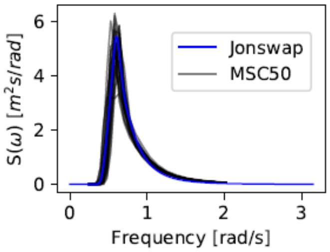

Figure 8 : Example of JONSWAP spectrum fit to storm spectra, used to evaluate spectral peakedness parameters.

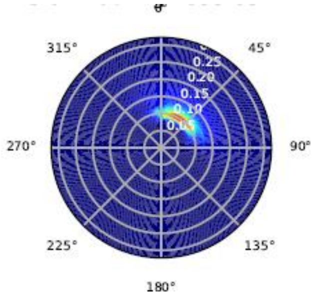

Figure 9 : Example of two-dimensional (frequency and direction) wave energy spectra. This was plotted to identify the directional distribution of different components of the sea states.

2.4 Results of Offshore Wind and Waves Analysis

The following sections summarize the results of offshore wind and wave analyses. Detail results for each analysis are shown in Appendix A. The offshore wave and wind analysis was processed using Python scripts. Python libraries such as numpy, WAFO and Matplotlib were used to perform data manipulation and statistical analysis, and to create plots. The scripts automate much of the analysis and allow repetition of the analysis for different MSC50 grid points, as the working numerical wave models are developed (in Phase 2).

2.4.1 Offshore Wind Climate

The wind and wave climate offshore of New Brunswick varies spatially according to geography (e.g. proximity to land masses), exposure to different types of meteorological phenomena, and available fetches. Separate regional numerical wave models were therefore developed (Section 3) to capture wave propagation and transformation within the Gulf of Saint Lawrence (Northern Region) and in the Bay of Fundy / Gulf of Maine (Southern Region) to the coast of New Brunswick. Offshore wind analysis results are discussed separately for each region in the following sub-sections.

Southern Region (Bay of Fundy / Gulf of Maine)

The offshore wind climate was analyzed at two MSC50 grid points for the southern part of New Brunswick. The first location was approximately 100 km south of Yarmouth, Nova Scotia in the

Atlantic Ocean (near the offshore boundary of the working numerical wave transformation model for this region – Phase 2) and the second was located in the center of the Bay of Fundy (to provide insight to wind conditions affecting local wave generation along fetches in the Bay of Fundy). Both locations are shown in Figure 10.

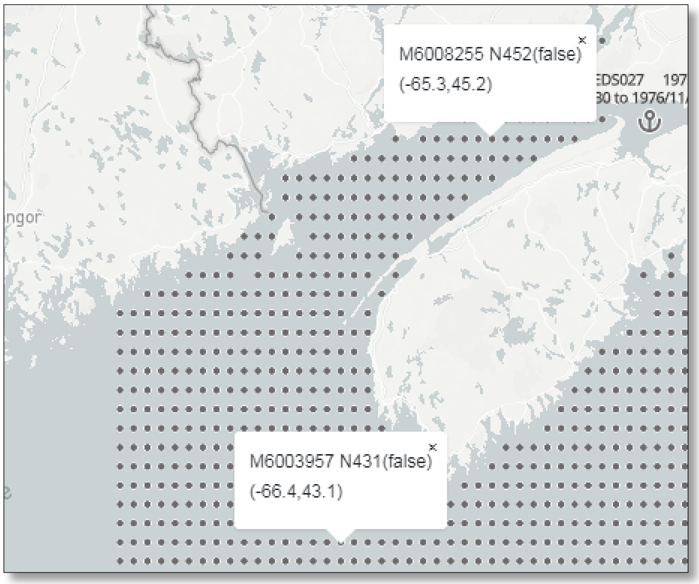

Figure 10: Offshore MSC50 data locations in the Southern Region.

Atlantic Ocean

The directional distribution of wind speeds above the 13.0 m/s threshold at the selected Atlantic Ocean grid point is shown in Figure 11. Offshore extreme wind speeds (1-hour average of the effective neutral wind at a height of 10 meters) blow from all directional sectors. Winds are typically strongest in late fall and winter (October through April), and predominantly coming from the west to northwest (W, WNW and NW sectors). Since these winds blow from the continent towards the ocean, they play a limited role in generating extreme waves along the New Brunswick coast. The extreme value analysis was therefore restricted to southerly sectors.

Southerly winds (from SE to WSW), blowing from the Atlantic Ocean into the Bay of Fundy and towards New Brunswick’s shoreline, are less frequent but occur throughout the year. These southerly winds can reach speeds of 20 to 30 m/s (72km/hr to 108km/hr) during extreme storms. Extreme offshore wind speeds for the grid point in the Atlantic Ocean off Yarmouth, Nova Scotia are summarized in Table 3, based on the statistical extreme value analysis described in Section 2.3.

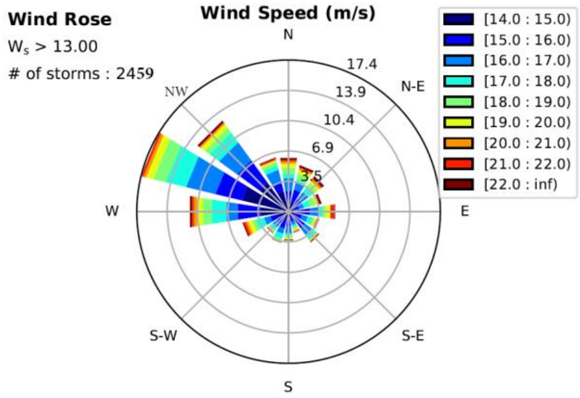

Figure 11: Wind rose of wind speeds above 13.0 m/s in the Atlantic Ocean (M6003957).

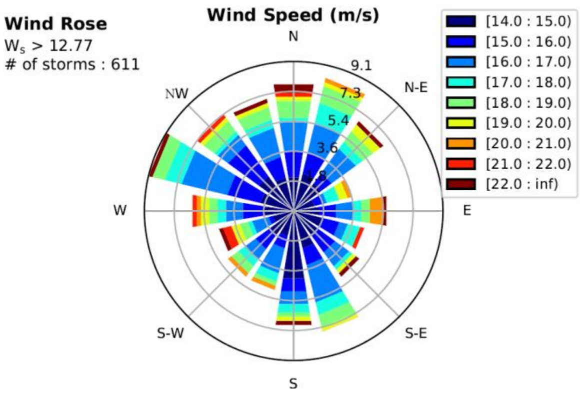

Figure 12: Wind rose of wind speeds above 12.8 m/s in the Bay of Fundy (M6008255).

Bay of Fundy

The directional distribution of wind speeds at the grid point in the Bay of Fundy is shown in Figure 12. Extreme wind speeds in the Bay of Fundy come from all directional sectors. The predominant winds are typically coming from the NW during late fall and winter months (December to March) and from the SSW during spring and summer months (April to September). Winds blow from both the SSW and NW sectors during a transition period in October and November. Extreme wind speeds based on a statistical analysis of storms are summarized in Table 3 for the grid point in the Bay of Fundy.

Table 3: Offshore extreme wind speeds (Southern Region)

Location	MSC50 Id	Return Period (years)	Wind Direction*	Wind Speed (m/s)
Atlantic Ocean	M6003957	**1, 100**	N to NE	18.2, 27.6
Atlantic Ocean	M6003957	**1, 100**	ENE to SSE	18.1, 29.2
Atlantic Ocean	M6003957	**1, 100**	SE to SW	17.4, 28.6
Atlantic Ocean	M6003957	**1, 100**	WSW to NNW	19.8, 29.6
Bay of Fundy	M6008255	**1, 100**	NNW to NE	15.7, 26.0
Bay of Fundy	M6008255	**1, 100**	ENE to SSE	13.5, 27.4
Bay of Fundy	M6008255	**1, 100**	SE to S	14.3, 24.8
Bay of Fundy	M6008255	**1, 100**	SSW to WSW	14.0, 24.5
Bay of Fundy	M6008255	**1, 100**	W to NW	14.9, 23.4

*(°, *"from"* clockwise true North)

Northern Region (Gulf of Saint Lawrence)

As for the southern region, MSC50 grid points were selected for analysis of extreme wind speeds in the Gulf of St. Lawrence (M6012085), Chaleur Bay (M6013134) and Northumberland Strait (M6010487), as shown in Figure 13.

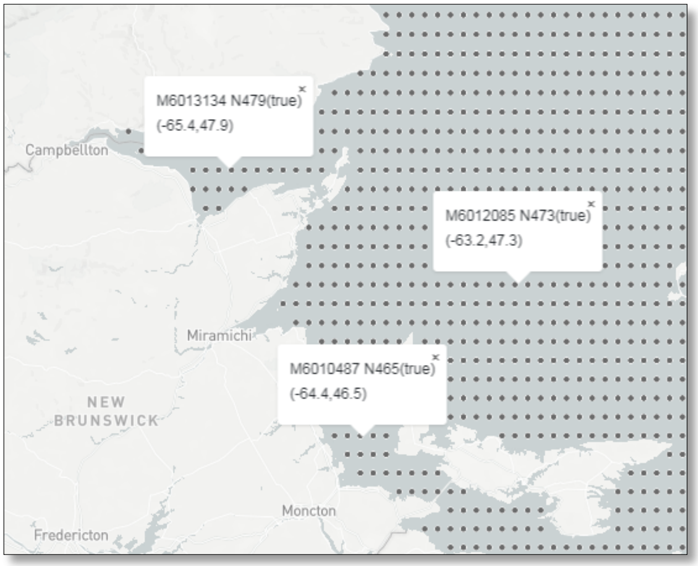

Figure 13: Offshore MSC50 data locations in the Northern Region.

Gulf of St. Lawrence

Offshore extreme wind speeds occur from all directional sectors except the SW sector (winds coming from the New Brunswick shore). Winds are typically strongest in late fall and winter (October through April) and predominantly blow from the west to northwest (W, WNW and NW sectors).

Northerly and easterly winds (from NNW to SSE), blowing from the Gulf of St. Lawrence towards the New Brunswick coast, are less frequent but present throughout the year. These winds can reach speeds of 25 m/s (90 km/hr) during extreme storms. The directional distribution of wind speeds in the Gulf of St. Lawrence is shown in Figure 14. The extreme offshore wind speeds, based on the statistical analysis described in Section 2.3, are summarized in Table 4.

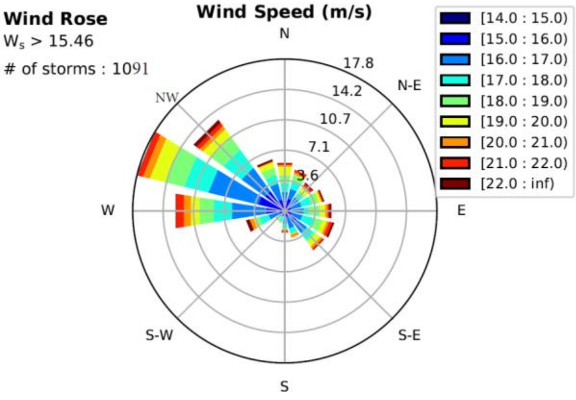

Figure 14: Wind Rose of wind speeds above 15.5 m/s in the Gulf of St. Lawrence (M6012085).

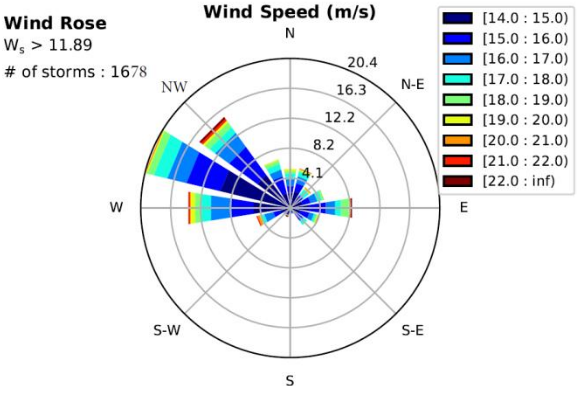

Figure 15: Wind Rose of wind speeds above 11.9 m/s in Chaleur Bay (M6013134).

Chaleur Bay

The directional distribution of wind speeds in Chaleur Bay is shown in Figure 15. Extreme winds in Chaleur Bay are predominantly from the northwesterly sectors (W to N). Winds are typically strongest from late fall to early spring (September through April). North-easterly (winds coming from the Gulf of St. Lawrence) are less frequent but present through the year. The extreme value analysis was only performed on four directional sectors. The extreme offshore wind speeds are summarized in Table 4.

Northumberland Strait

The directional distribution of wind speeds in Northumberland Strait is shown in Figure 16. Extreme winds blow from all directional sectors except the SW sector (winds blowing from the New Brunswick shore). Winds are typically strongest in late fall to early spring (October through April) and predominantly come from the west to northwest (W, WNW and NW sectors). South-easterly winds are less frequent but present through the year. Extreme value analyses were performed using storm data for five directional sectors. The extreme offshore wind speeds are summarized in Table 4.

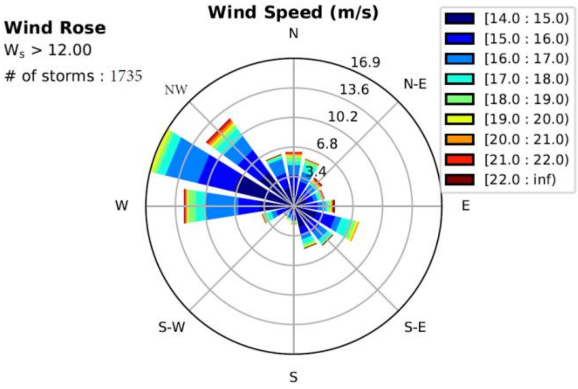

Figure 16: Wind Rose of wind speed above 12.0 m/s in Northumberland Strait (M6010487).

Table 4: Offshore extreme wind speeds (Northern Region)

Location	MSC50 Id	Return Period (years)	Wind Direction*	Wind Speed (m/s)
Gulf of St. Lawrence	M6012085	**1, 100**	N to NE	17.8, 24.4
Gulf of St. Lawrence	M6012085	**1, 100**	ENE to SE	18.7, 28.0
Gulf of St. Lawrence	M6012085	**1, 100**	SSE to SW	16.2, 26.5
Gulf of St. Lawrence	M6012085	**1, 100**	WSW to NNW	20.1, 25.7
Chaleur Bay	M6013134	**1, 100**	N to NE	14.8, 21.8
Chaleur Bay	M6013134	**1, 100**	ENE to SSE	15.2, 24.9
Chaleur Bay	M6013134	**1, 100**	SE to SW	13.5, 22.4
Chaleur Bay	M6013134	**1, 100**	WSW to NNW	17.3, 24.6
Northumberland Strait	M6010487	**1, 100**	NNW to NNE	15.6, 22.6
Northumberland Strait	M6010487	**1, 100**	NE to E	14.7, 27.2
Northumberland Strait	M6010487	**1, 100**	ESE to SSE	15.4, 24.6
Northumberland Strait	M6010487	**1, 100**	S to WSW	14.3, 27.2
Northumberland Strait	M6010487	**1, 100**	W to NW	16.8, 25.5

*(°, *"from"* clockwise true North)

2.4.2 Offshore Wave Climate

Offshore wave analysis results are discussed separately for the previously identified Southern and Northern Regions in the following sub-sections. The MSC50 grid points selected for the extreme wave analysis are identical to those selected for the wind analysis, except where otherwise indicated.

Southern Region (Atlantic Ocean)

The offshore wave climate was analyzed for an MSC50 grid point located approximately 100 km south of Yarmouth, NS in the Atlantic Ocean. This is the same location as the one studied in the offshore wind analysis (MSC50 Id=M6003957), as shown in Figure 10. Grid point M6003493, the closest MSC50 grid point where spectral wave data was available, was selected to analyze the directional wave spectra.

Most storm sea states contain energy from both wind sea (i.e. locally generated, high frequency) and swell sea (low frequency) components. During storms (nominally defined as significant wave heights exceeding 3 m), wind sea propagates predominantly towards the ocean (ENE to SE), as shown in Figure 17, consistent with the dominant winds coming from the west described in Section 2.4.1. Extreme swells generated by distant oceanic storms propagate predominantly towards the WNW to N sectors, and the Bay of Fundy (Figure 18).

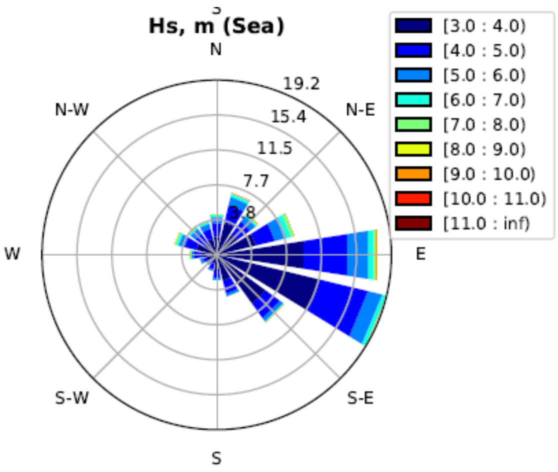

Figure 17: Wave rose of significant wave heights above 3 m associated with wind sea (M6003957).

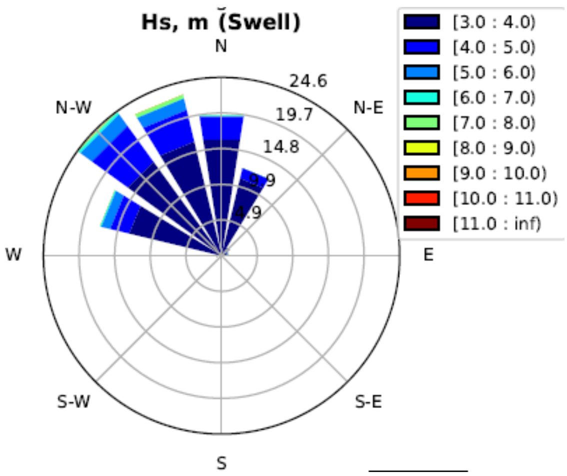

Figure 18: Wave rose of significant wave heights above 3 m associated with swell sea (M6003957).

Figure 19 shows an example of a typical directional energy spectrum. The energy generated by the wind, highlighted by a red box, is propagating towards the west and the swell energy, highlighted by a green box, is propagating towards the north.

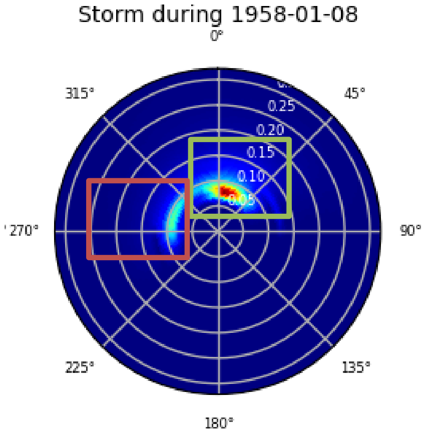

Figure 19 : Example of a typical directional energy spectrum

Extreme values (significant wave heights and peak wave periods) were analyzed for different sea-state conditions (wind-sea and swell-sea) with two groups of directional sectors (W to N and NNE to E). The appropriate spectral parameters were identified based on the extreme significant wave height and extreme period. The extreme values are summarized in Table 5.

Table 5: Offshore extreme significant wave height, peak wave period, directional spreading and spectral peakedness, M6003957 (Southern Region)

Return Period (years)	Sea-State	Wave Direction*	Significant Wave Height (m)	Peak Wave Period (s)	Directional Spreading (°)	Spectral Peakedness (-)
1	Wind Sea	NNE to NE	4.8	9.6	45-50	1.5-2.5
100	Wind Sea	NNE to NE	10.6	14.4	45-50	1.5-2.5
1	Wind Sea	ENE to SSE	6.0	10.3	45-50	1.5-2.5
100	Wind Sea	ENE to SSE	10.0	12.1	45-50	1.5-2.5
1	Wind Sea	S to WSW	4.1	8.0	45-50	1.5-2.5
100	Wind Sea	S to WSW	6.7	11.0	45-50	1.5-2.5
1	Wind Sea	W to N	5.4	10.0	45-50	1.5-2.5
100	Wind Sea	W to N	9.4	13.1	45-50	1.5-2.5
1	Swell Sea	W to N	4.5	11.8	45-50	1.5-2.5
100	Swell Sea	W to N	8.5	16.0	45-50	1.5-2.5

*(°, *"to"* clockwise true North)

Northern Region (Gulf of Saint Lawrence)

The offshore wave climate was analyzed for an MSC50 grid point in the Gulf of St. Lawrence (M6013642) as shown in Figure 13. This grid point included full directional wave spectra. Extreme waves in the Gulf of Saint Lawrence are predominantly generated by local winds and propagate towards the New Brunswick coastline (through the E to NW sectors) as shown in Figure 20. Extreme waves associated with the swell component of the wave spectrum infrequently exceed wave heights of 5 m. Swell predominantly propagates towards the SW to W sectors (Figure 21).

Extreme values (significant wave heights and peak wave periods) were analyzed for different sea-state conditions (wind-sea and swell-sea) with one group of directional sectors (SE to WNW). The appropriate spectral parameters was identify based on the on the extreme significant wave height and extreme period. The extreme values are summarized in Table 6.

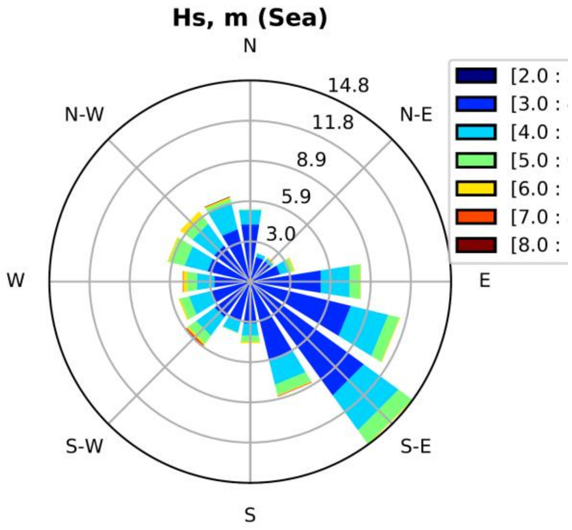

Figure 20: Wave rose of significant wave height above 2 m associated with wind sea (M6013642).

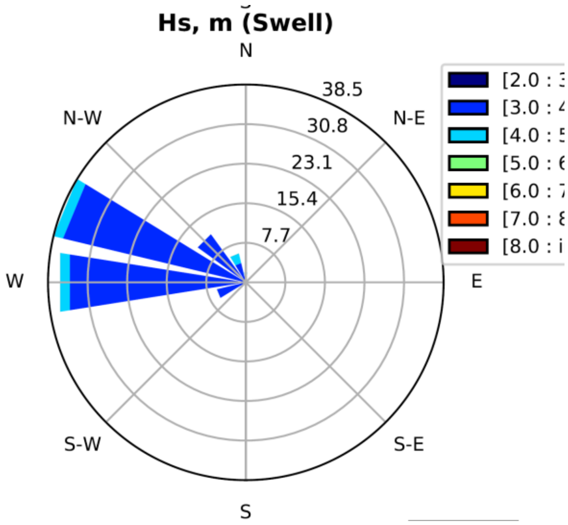

Figure 21: Wave rose of significant wave heights above 2 m associated with swell sea (M6013642).

Table 6: Offshore extreme significant wave height, peak wave period, directional spreading and spectral peakedness, M6013642 (Northern Region)

Return Period (years)	Sea State	Wave Direction*	Significant Wave Height (m)	Peak Wave Period (s)	Directional Spreading (°)	Spectral Peakedness (-)
1	Wind Sea	N to ENE	3.8	8.0	45-50	2.0-3.0
100	Wind Sea	N to ENE	7.8	10.9	45-50	2.0-3.0
1	Wind Sea	E to SSE	5.1	9.2	45-50	2.0-3.0
100	Wind Sea	E to SSE	7.3	10.8	45-50	2.0-3.0
1	Wind Sea	S to SW	3.7	8.0	45-50	2.0-3.0
100	Wind Sea	S to SW	6.7	10.2	45-50	2.0-3.0
1	Wind Sea	SW to W	4.8	4.1	45-50	2.0-3.0
100	Wind Sea	SW to W	8.4	12.1	45-50	2.0-3.0
1	Wind Sea	WNW to NNW	4.8	9.0	45-50	2.0-3.0
100	Wind Sea	WNW to NNW	8.0	11.0	45-50	2.0-3.0

*(°, *"to"* clockwise true North)

3 Nearshore Waves

A wave transformation study was implemented using the SWAN numerical model to develop estimates of extreme (storm) wave conditions in the New Brunswick nearshore area. The following sub-sections describe the approach, inputs, methodology and results of the wave transformation study.

3.1 Overview of Modelling Approach

The wave transformation modelling presented in the following sub-sections was implemented using SWAN (Cycle III version 41.20A), a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters [9] [10] [11]. SWAN (Simulating WAves Nearshore) was developed by Delft University of Technology, is distributed under GNU General Public License, and is extensively used and applied worldwide. The model accounts for the following physical processes:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth;
- Wave generation by wind;
- Triad and quadruplet wave-wave interactions;
- Whitecapping, bottom friction and depth-induced breaking;
- Wave-induced set-up;
- Propagation from laboratory up to global scales; and
- Transmission through and reflection (specular and diffuse) against obstacles.

Several SWAN wave transformation models were set up incorporating topography and bathymetry data from a number of sources. Offshore wind and wave conditions obtained from the MSC50 hindcast database (Section 2) were used to drive the numerical models and transform offshore and locally generated wind waves to the New Brunswick nearshore. The models were run in quasi-stationary mode (i.e. sequential, stationary simulations) for calibration and validation against temporally varying wave buoy data, and in stationary (steady) mode for probabilistic scenarios (1 year and 100 year return period events). Water levels were input to the model based on the values determined by R.J. Daigle Enviro for 14 identified coastal zones in New Brunswick [3], which incorporate storm surge and allowances for projected sea level rise to the year 2100.

3.2 Model Setup

3.2.1 Model Domains

The SWAN wave transformation models were set up using an uncoupled nested approach, whereby a series of rectangular grids were used to generate boundary conditions for input to successively finer resolution grids. This allowed for capturing the effects of shoals, channels and other detailed seabed features that influence wave transformation in nearshore waters of New Brunswick. The extents of the SWAN computational grids for the Southern and Northern Regions are shown in Figure 22 and Figure 23, respectively.

The system of nested models for the Southern Region consisted of a 500m resolution grid covering the entire Bay of Fundy and extending into the Gulf of Maine, a nested 300m resolution grid covering the Bay of Fundy, and three 100m resolution grids nested within the Bay of Fundy model.

The system of nested models for the Northern Region consisted of a 300m resolution regional grid extending from Northumberland Strait to Chaleur Bay and into the Gulf of Saint Lawrence, with three nested model subdomains providing enhanced (100m) resolution in coastal waters of Chaleur Bay (Zones 1, 2 and 3), Zones 4-6, and Northumberland Strait (Zones 7-10), respectively.

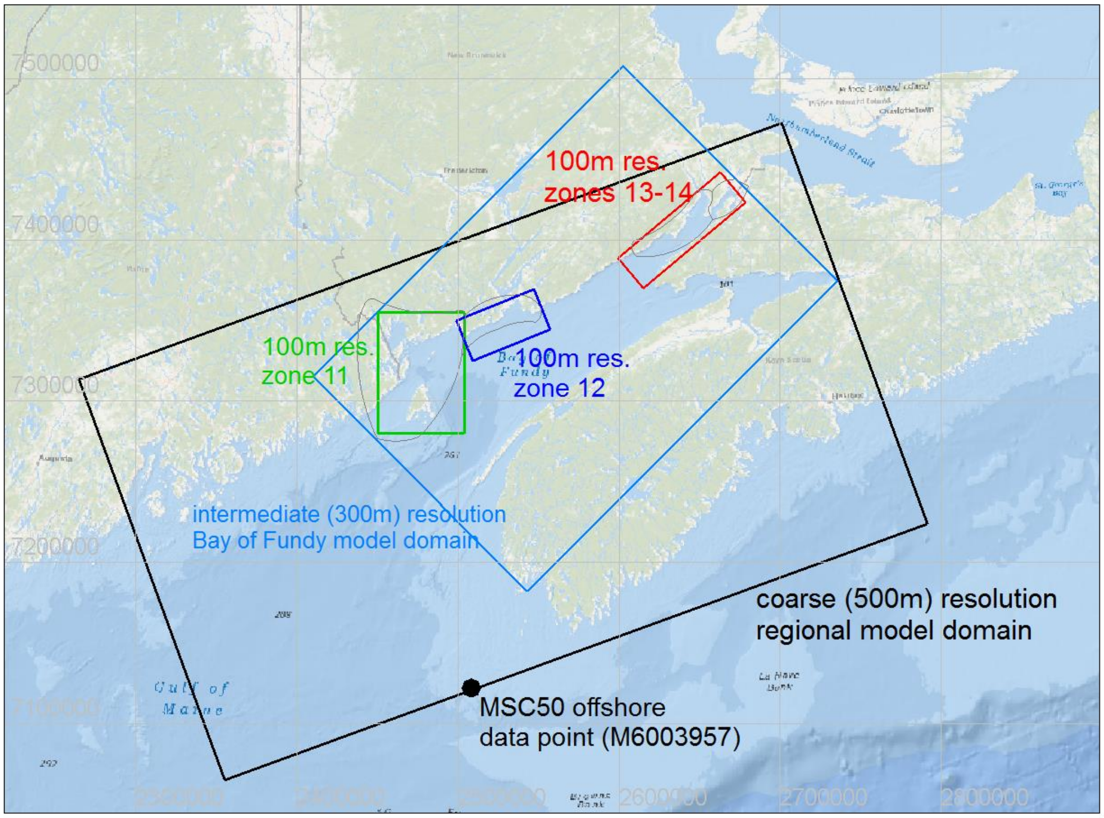

Figure 22. Southern Region SWAN model domain and nested sub-domains.

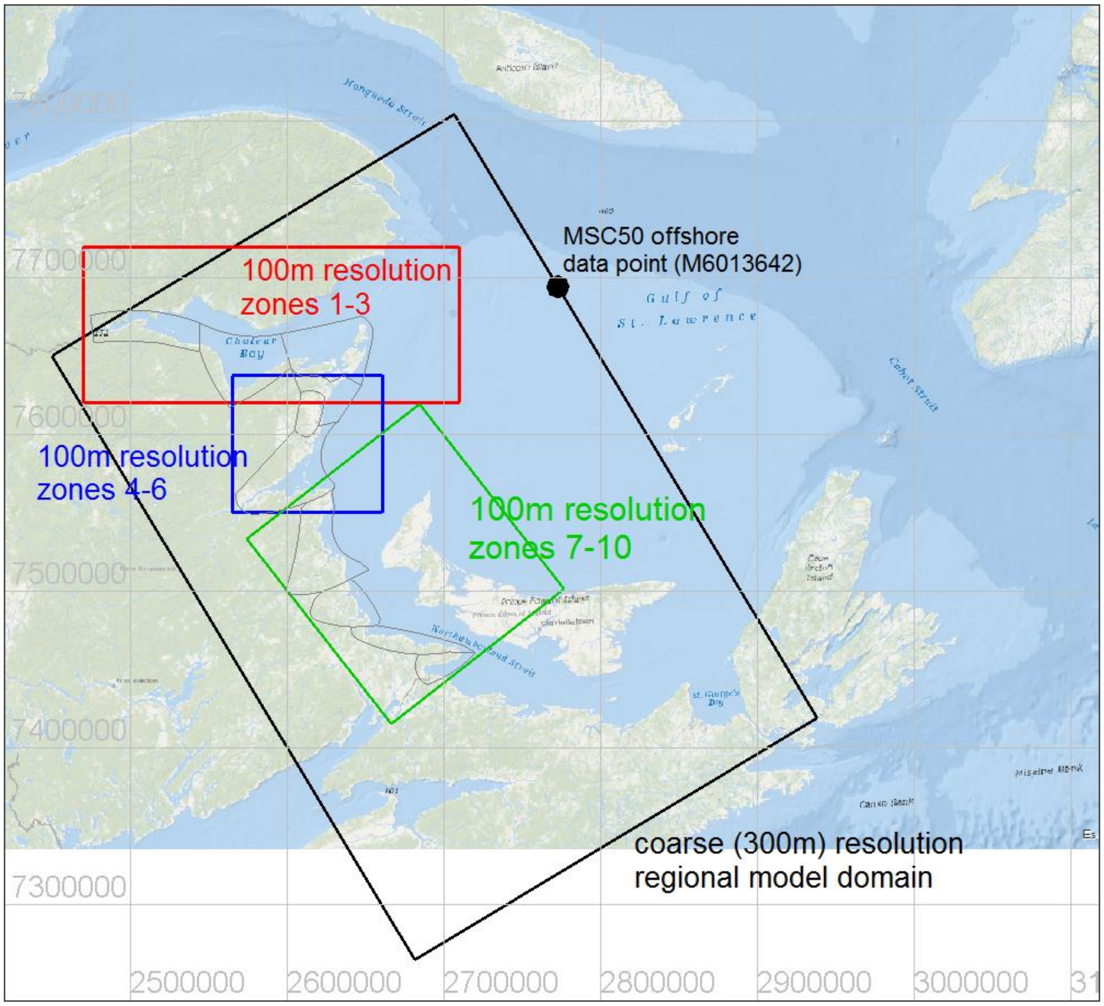

Figure 23. Northern Region SWAN model domain and nested sub-domains.

3.2.2 Topography

Three datasets were used to provide topographic input to the model along the New Brunswick coast, in the following hierarchical order (depending on availability, coverage and quality of the data) based on the reported accuracy:

1. High resolution (1m) LiDAR data, downloaded from the GeoNB website, resampled to 50m horizontal resolution;
2. 30m resolution Canadian Digital Elevation Model (CDEM) data, downloaded from the Government of Canada open data portal;
3. A 70m resolution Digital Terrain Model (DTM) for the Province of New Brunswick, downloaded from the GeoNB website.

The datasets were normalized to Canadian Geodetic Vertical Datum of 1928 (CGVD28), buffered to within a distance of 2km of the coast (based on NOAA vector shorelines), and truncated below intertidal elevations (+5.5 mCGVD28 in the Southern Region and in the range +0.5 to +1.5 mCGVD28 in the Northern Region). The latter measure was taken to remove LiDAR data in areas where the sea surface was detected and to eliminate areas of overlap with CHS bathymetry data (Section 3.2.3).

3.2.3 Bathymetry

Bathymetric data was licensed to NRC by the Canadian Hydrographic Service (CHS) for the purpose of the study. This included:

- High resolution (ranging from 5 to 20m horizontal resolution) multi-beam bathymetric survey data;
- Single-beam bathymetric survey soundings; and
- Soundings from electronic navigation charts (ENCs).

The CHS bathymetry data was transformed from local Chart Datum (CD) to CGVD28 using output from the hydrographic vertical separation surface (HyVSEP), which provides the separation between CD and CGVD28 at discrete points in Canadian tidal waters [12]. The CHS data was supplemented by GEBCO_2014 (30 arc-second resolution) gridded bathymetric data [13] in offshore areas outside Canadian coastal waters (e.g. in the Gulf of Maine).

The SWAN model computational grids, incorporating merged and interpolated topographic and bathymetric data as described above, are shown in Figure 24 (Southern Region) and Figure 25 (Northern Region). Artificial land was introduced in some areas (e.g. areas shown in grey to the east of Nova Scotia in Figure 24) to eliminate computations in grid cells not affecting wave conditions in areas of interest, thereby enhancing computational efficiency.

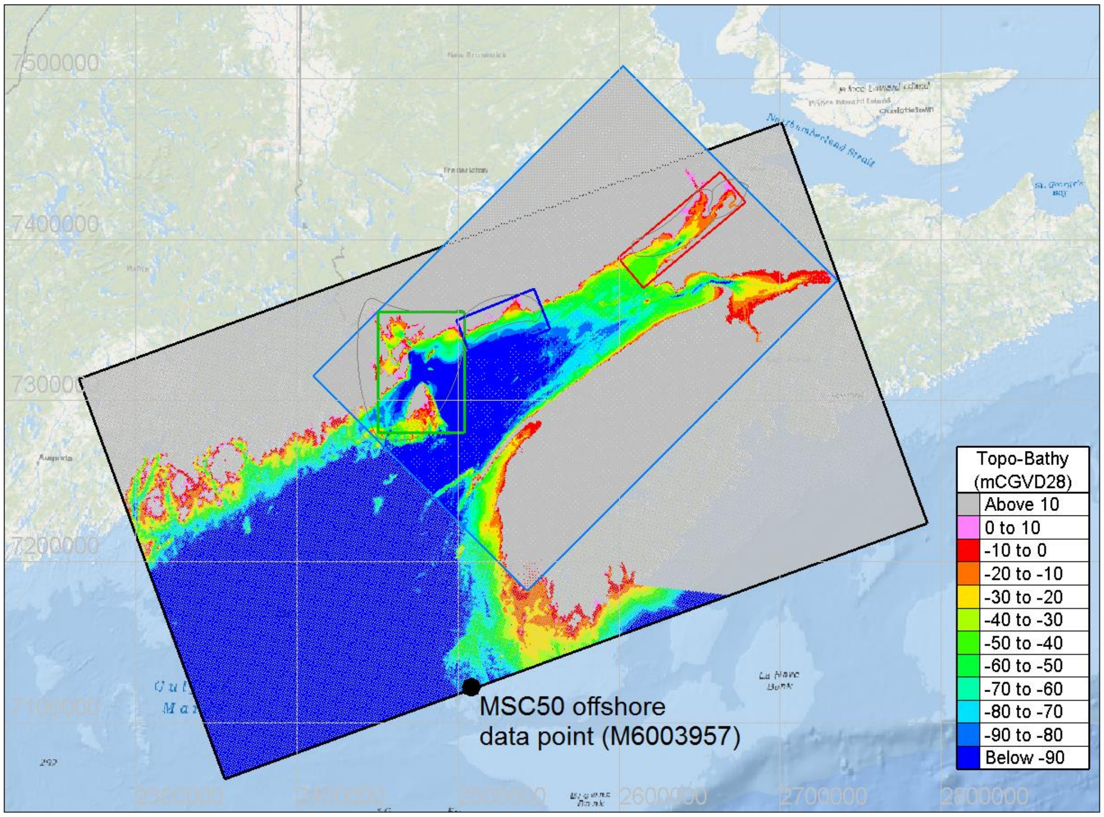

Figure 24. Southern Region SWAN computational grids and topography-bathymetry.

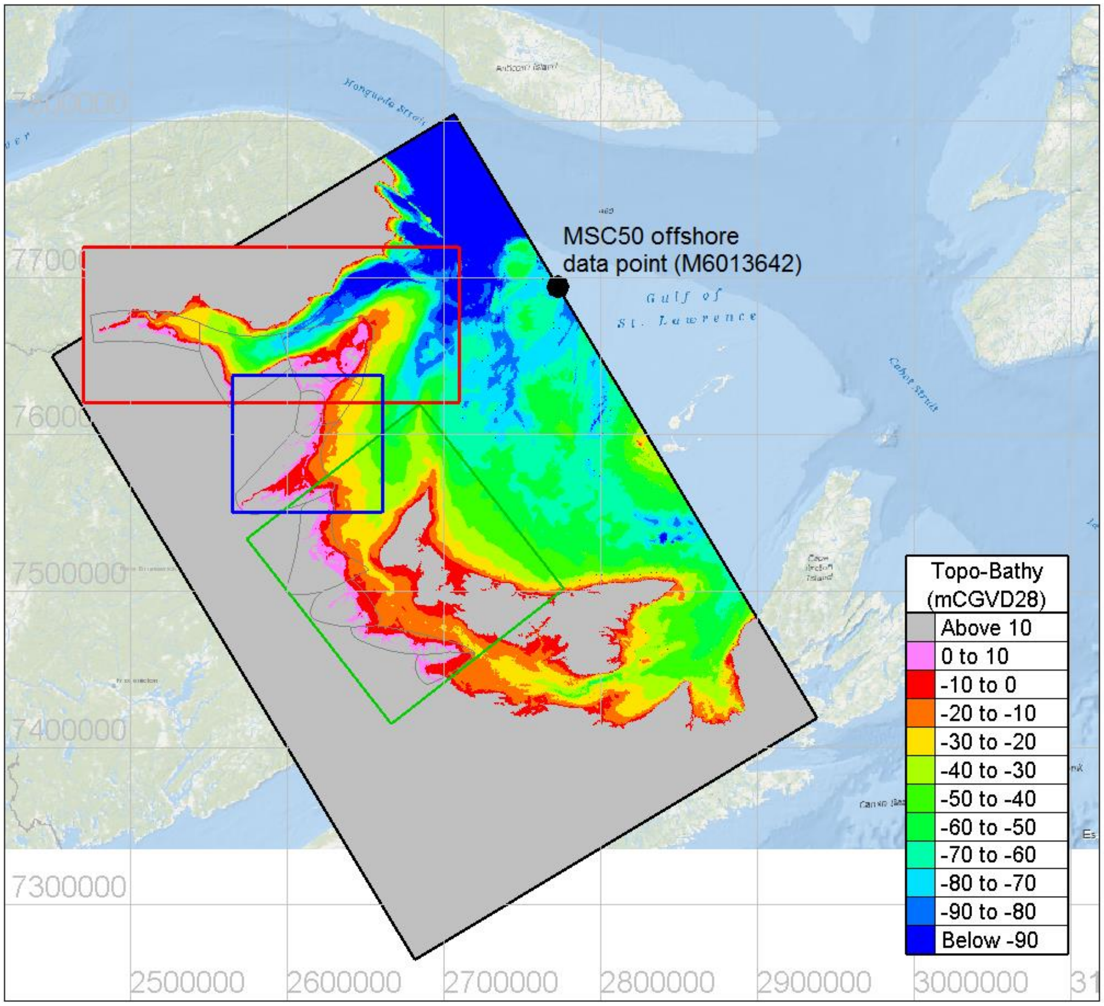

Figure 25. Northern Region SWAN computational grids and topography-bathymetry.

3.2.4 Boundary Conditions

Boundary conditions applied to the SWAN numerical wave models include:

- Waves;
- Water levels;
- Wind; and
- Bed friction.

Further details of each of the applied boundary conditions are described in the following sub-sections.

Waves

The offshore wave conditions presented in Section 2.4.2 were applied at all seaward open sea boundaries of the regional (coarse resolution) models. Open sea boundary conditions for the nested (intermediate and fine resolution) models were extracted directly from the results of the coarse resolution model simulations.

JONSWAP-type wave spectra with significant wave heights ($H_s \approx H_{m0}$), peak wave periods (T_p) and peak wave directions (θ_p)[1] were specified at the offshore boundaries of the regional model. The spectral peakedness factor (γ_{JON}) and the power of the cosine spreading function (n) were specified based on the directional spreading and peakedness determined from the analysis of the MSC50 database described in Section 2.3.3.

Water Levels

For quasi-stationary model simulations of storms (during calibration and validation), time-varying water levels were specified based on historical observations at CHS tide gauges (Saint John in the Southern Region and Escuminac in the Northern Region), downloaded from the Fisheries and Oceans Canada online archive (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/maps-cartes/inventory-inventaire-eng.asp).

For production simulations (i.e. 1 and 100 year return period events), constant water levels were input to the model based on the upper bound values for each of the 14 coastal flood hazard zones in New Brunswick identified by R.J. Daigle Enviro [8], which incorporate storm surge and sea level rise to the year 2100. Water levels were assumed to be spatially uniform throughout the model domains and values associated with the 2100 time horizon were applied in combination with the corresponding wind/wave return period. This assumes wind/waves and water levels are strongly correlated. This is a typical assumption in the absence of long-term, co-located and coincident water level and wave data to support a joint probability analysis, based on the premise that extreme high water levels are usually the result of strong onshore winds, which are typically also associated with storm waves. For the regional (coarse resolution) and nested intermediate resolution models, water level boundary conditions were specified based on the highest zonal return values in each region, providing for conservative[2] estimates of wave heights at the local (fine resolution) nested model boundaries. Water level boundary conditions were applied to the fine resolution models based on zone-specific return values, to properly account for wave transformation and dissipation in nearshore areas where water levels have the most significant impact on wave conditions. Where fine resolution models encompassed multiple zones, the highest zonal water level was applied.

Wind

Stationary, uniform wind fields were applied based on MSC50 wind speeds and directions at the offshore boundary of the regional model domains. Initially (during model calibration), wind speeds were applied based on MSC50 data points close to the centre of the model domain. However, this resulted in underestimation of nearshore significant wave heights compared to wave buoy data. Wind fields based on the offshore data resulted in better agreement between SWAN model output and measured wave buoy data.

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[1] Note that, by default, wave directions in SWAN are expressed in the nautical convention (i.e. the direction from which the waves are propagating, expressed in degrees measured positive clockwise from true north). This is the convention adhered to in this Section but it should be recognized that it is different to the convention used in Section 2 when referring to the MSC50 database (which refers to the direction towards which waves propagate).

[2] Higher water levels generally correspond to higher waves in nearshore areas, as waves propagating towards the shore are less susceptible to dissipation by bed friction and depth-induced wave breaking processes.

For production simulations involving transformation of swell and wind sea from offshore to nearshore, wind fields were assumed to be co-directional with the peak wave direction at the offshore boundary of the regional model. Wind speeds were based on a linear regression of values associated with storm peak significant wave heights at the relevant MSC50 grid points, analyzed separately for each directional sector (Table 5 and Table 6). Where the regressed wind speeds exceeded return values based on the extreme value analyses described in Section 2.3.2, the return values were applied as an upper bound. For simulations implemented to assess waves generated by local winds blowing over the model domains, wind speed return values were applied based on the statistical analysis of wind data described in Section 2.3.2.

Bed Friction

Bottom friction was activated in the SWAN model using the JONSWAP formulation [9]. The value of the friction coefficient, c_{JON}, was adjusted within the recommended range 0.019 m^2s^{-3} to 0.067m^2s^{-3} during calibration. A value of 0.019m^2s^{-3} resulted in the closest agreement between modelled and measured storm peak significant wave heights.

3.2.5 Other Model Input Parameters

Other non-default model input parameters included:

- Depth-induced wave breaking. Dissipation of wave energy due to depth-induced breaking is represented in SWAN by the bore-based model of Battjes and Janssen [14]. This model requires the user to specify the breaker index (γ), which defines the maximum wave height supported in a given water depth. A constant breaker index, γ, equal to 0.7 was specified based on values in the range 0.58 to 0.72 provided by three different breaker index models [15] [16] [17];
- Diffraction. Diffraction is a physical process by which wave energy is transmitted or bends into the leeward region of an obstacle, such as an island or breakwater. Diffraction effects can be approximated in SWAN using a phase-decoupled refraction-diffraction scheme [18]. This functionality was activated in the nested intermediate and fine resolution SWAN models to account for diffraction effects on wave fields in the lee of islands and headlands in the New Brunswick nearshore (e.g. Fundy Islands, Prince Edward Island);
- Nonlinear wave-wave interactions. These are processes by which resonant sets of wave components in a sea state interact, redistributing energy over the frequency spectrum [14]. “Quadruplet” wave-wave interactions, which are important in deep water, are activated by default in SWAN. “Triad” nonlinear wave interactions were activated (non-default option) to reflect the importance of these processes in shallow coastal waters.

3.3 Model Testing and Verification

3.3.1 Calibration and Validation

Calibration of the SWAN models involved simulating (in quasi-stationary mode) a series of storms and comparing model output parameters (significant wave heights and peak wave periods) with available wave buoy measurements from Fisheries and Oceans Canada archives (Section 2.2). The storms and simulation periods selected for calibration and validation were constrained by the availability of wave buoy data at locations within the model domains. Model input parameters, such as bed friction, were adjusted within appropriate ranges to identify values providing the best agreement (based on visual inspection of time series) between modelled and measured parameters. Following model calibration and optimization of input parameters, an additional series of storms were simulated. The model output was again compared to wave buoy measurements to re-assess (visually) the goodness-of-fit (i.e. validation). Comparisons of measured and modelled storm significant wave heights at several locations within the model domains are presented in Figure 26 to Figure 28, for scenarios incorporating the final model parameter selections. The availability of long-term wave buoy measurements in the region limits the extent to which calibration / validation can be performed. For example, the model underpredicts peak significant wave heights at Gannet Rock during the 1997 storm (Figure 27). This is a direct result of the underprediction of peak significant wave heights by the MSC50 hindcast database for this particular event (based on a comparison with offshore buoys). However, for cases where the MSC50 output is in better agreement with offshore wave measurements (e.g. the 1976 event), the nested SWAN models, running in stationary mode, are capable of capturing peak storm significant wave heights in New Brunswick nearshore areas. This provides some confidence in the SWAN model's capability to estimate probabilistic extremes (i.e. 1 year and 100 year return period conditions), assuming the MSC50 data is statistically representative over longer periods of time (as demonstrated by Swail et al. [6]).

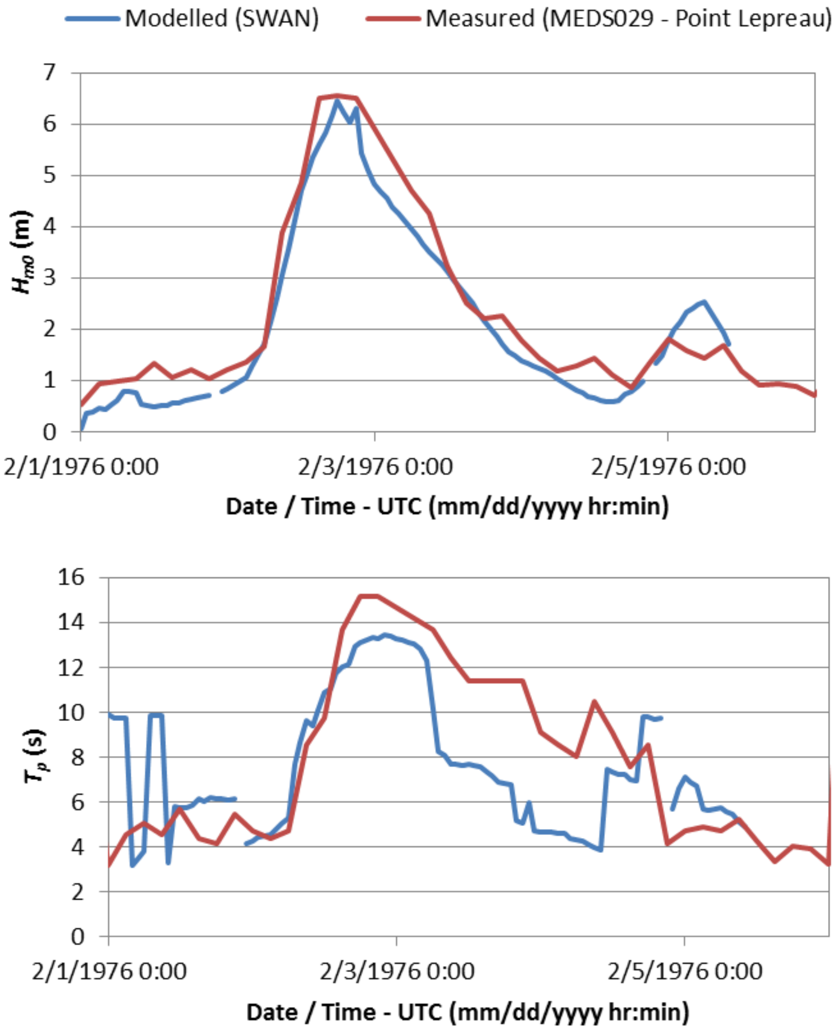

Figure 26. Measured and modelled significant wave heights and peak wave periods at Point Lepreau during a 1976 storm in the Bay of Fundy.

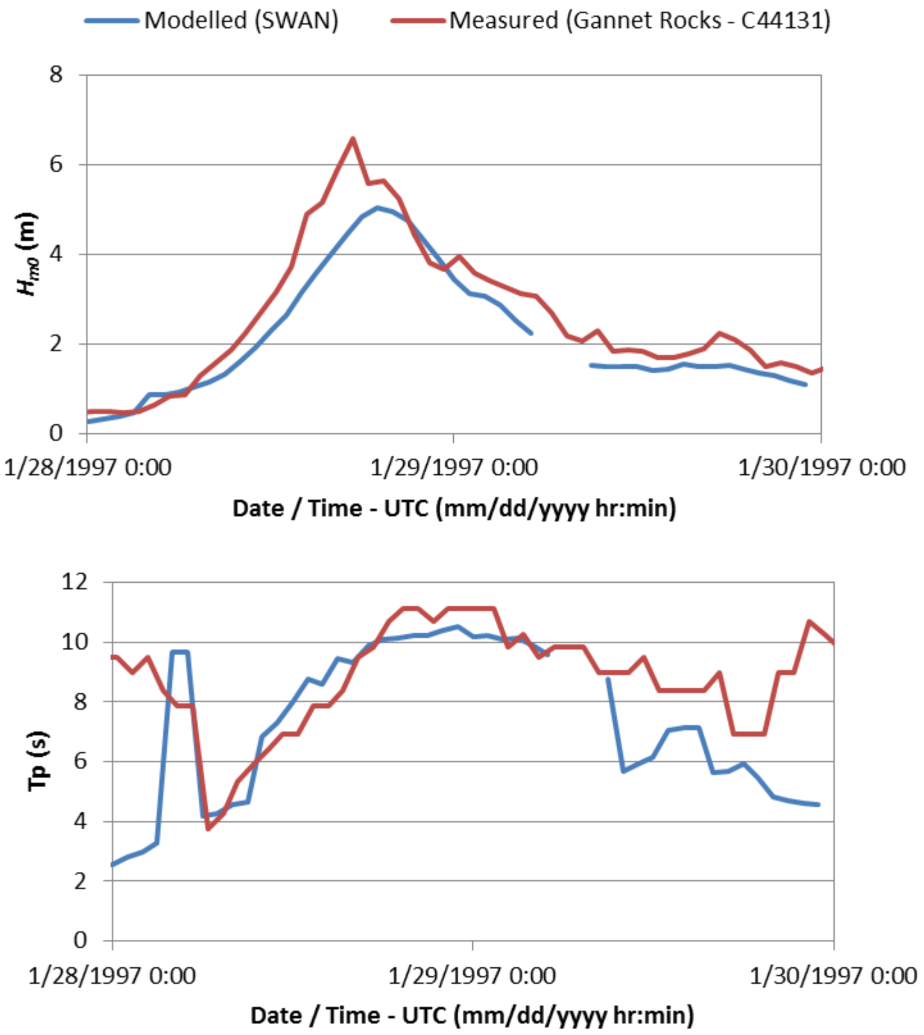

Figure 27. Measured and modelled significant wave heights and peak wave periods at Gannet Rocks during a 1997 storm in the Bay of Fundy.

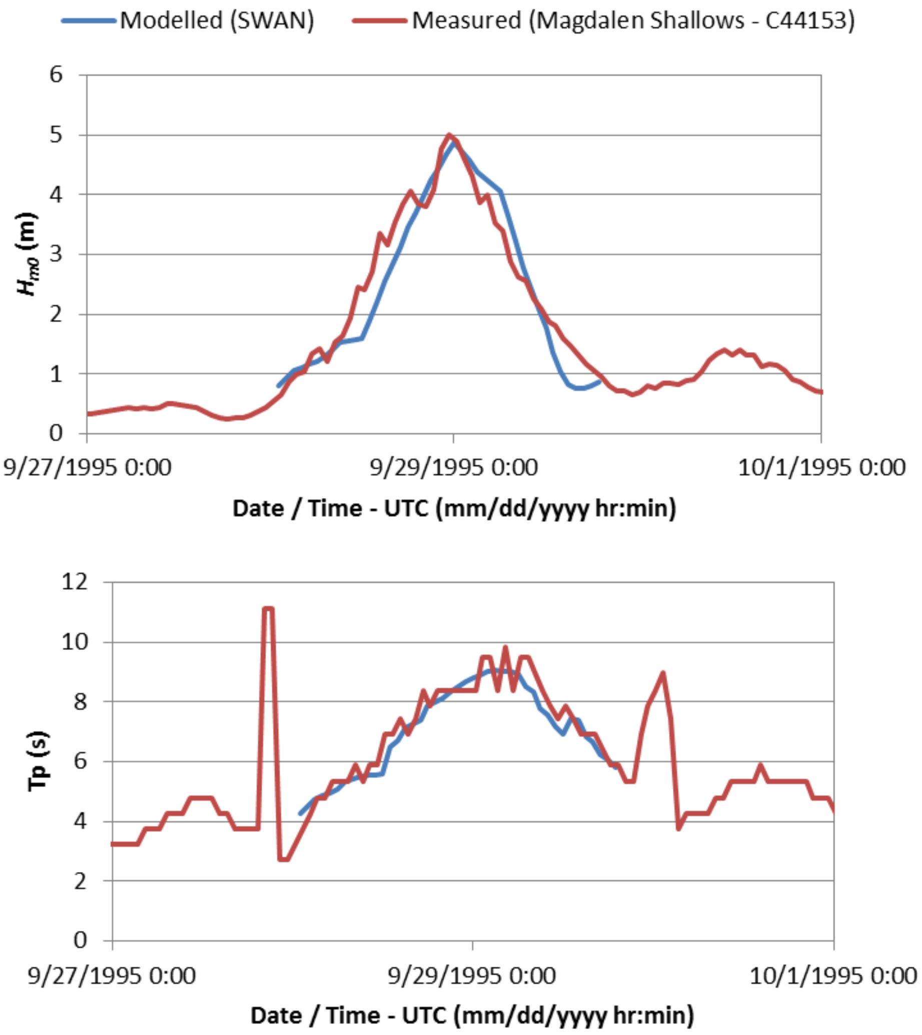

Figure 28. Measured and modelled significant wave heights and peak wave periods at Magdalen Shallows during a 1995 storm in the Gulf of Saint Lawrence.

3.3.2 Sensitivity Tests

A number of stationary wave transformations were performed to investigate the sensitivity of the models to various input parameters, including:

- Wave breaking parameters. The breaker index, γ, which determines the limit of depth-induced wave breaking. Values in the range 0.6 to 0.73 (SWAN default value) were investigated;
- Bed friction. Model outputs for the SWAN default friction coefficient $c_{JON} = 0.038\ m^2s^{-3}$ were compared to outputs based on the calibrated value ($0.019\ m^2s^{-3}$); and
- Water levels. Model outputs based on the zonal average water level were compared to baseline scenarios, in which the zonal maximum was applied as the reference water level. Sensitivity tests were also conducted using 2010 water levels (as opposed to the 2100 baseline water levels), to explore the effects of sea level rise allowances on nearshore wave conditions.

3.4 Wave Transformations (Production Simulations)

Stationary wave transformations were performed using the calibrated and validated SWAN models, using the 1 year and 100 year return period wave, wind and water level conditions described in Sections 2.4.1, 2.4.2, 3.2 and 3.2.5 as input. The full schedule of simulations is listed in Table 7 (for the Southern Region) and Table 8 (for the Northern Region) based on the input wind, wave and water level conditions.

Table 7: Schedule of wave transformation model simulations (Southern Region)

Simulation ID	Return Period (years)	Water Level* (mCGVD28)	Offshore Wave Conditions			Offshore Wind Conditions	
			H_{m0} (m)	T_p (s)	θ_p (°)	*Ws* (m/s)	*Wd* (°)
NB_S_001	1	9.9	5.4	10	90	15.1	90
NB_S_002	100	10.4	9.4	13	90	26.3	90
NB_S_003	1	9.9	4.5	12	90	12.6	90
NB_S_004	100	10.4	8.5	16	90	23.8	90
NB_S_005	1	9.9	5.4	10	112.5	15.1	112.5
NB_S_006	100	10.4	9.4	13	112.5	26.3	112.5
NB_S_007	1	9.9	4.5	12	135	12.6	135
NB_S_008	100	10.4	8.5	16	135	23.8	135
NB_S_009	1	9.9	5.4	10	180	15.1	180
NB_S_010	100	10.4	9.4	13	180	26.3	180
NB_S_011	1	9.9	4.5	12	180	12.6	180
NB_S_012	100	10.4	8.5	16	180	23.8	180
NB_S_013	1	9.9	4.8	10	202.5	13.5	202.5
NB_S_014	100	10.4	10.6	14	202.5	28.6	202.5
NB_S_015	1	9.9	4.8	10	225	13.5	225
NB_S_016	100	10.4	10.6	14	225	28.6	225
NB_S_017	1	9.9	0	0	n/a	15.7	45
NB_S_018	100	10.4	0	0	n/a	26.0	45
NB_S_019	1	9.9	0	0	n/a	13.5	67.5
NB_S_020	100	10.4	0	0	n/a	27.4	67.5
NB_S_021	1	9.9	0	0	n/a	13.5	90
NB_S_022	100	10.4	0	0	n/a	27.4	90
NB_S_023	1	9.9	0	0	n/a	14.3	135
NB_S_024	100	10.4	0	0	n/a	24.8	135
NB_S_025	1	9.9	0	0	n/a	14.3	180
NB_S_026	100	10.4	0	0	n/a	24.8	180
NB_S_027	1	9.9	0	0	n/a	14.0	202.5
NB_S_028	100	10.4	0	0	n/a	24.5	202.5

*Water levels shown reflect highest values applied, i.e. as boundary condition input to coarse resolution (regional) models.

Table 8: Schedule of wave transformation model simulations (Northern Region)

Simulation ID	Return Period (years)	Water Level* (mCGVD28)	Offshore Wave Conditions			Offshore Wind Conditions	
			H_{m0} (m)	T_p (s)	θ_p (°)	*Ws* (m/s)	*Wd* (°)
NB_N_001	1	3.4	3.7	8	0	16.4	0
NB_N_002	100	4.7	6.7	10	0	24.4	0
NB_N_003	1	3.4	3.7	8	45	16.4	45
NB_N_004	100	4.7	6.7	10	45	24.4	45
NB_N_005	1	3.4	4.8	9	45	16.4	45
NB_N_006	100	4.7	8.4	12	45	24.4	45
NB_N_007	1	3.4	4.8	9	67.5	16.4	67.5
NB_N_008	100	4.7	8.4	12	67.5	24.4	67.5
NB_N_009	1	3.4	4.8	9	90	15.0	90
NB_N_010	100	4.7	8.4	12	90	21.1	90
NB_N_011	1	3.4	4.8	9	112.5	15.0	112.5
NB_N_012	100	4.7	8.0	11	112.5	21.1	112.5
NB_N_013	1	3.4	4.8	9	157.5	12.3	157.5
NB_N_014	100	4.7	8.0	11	157.5	20.0	157.5
NB_N_015	1	3.4	5.1	9	337.5	17.6	337.5
NB_N_016	100	4.7	7.3	11	337.5	22.9	337.5
NB_N_017	1	3.4	0	0	n/a	17.8	0
NB_N_018	100	4.7	0	0	n/a	24.4	0
NB_N_019	1	3.4	0	0	n/a	17.8	45
NB_N_020	100	4.7	0	0	n/a	24.4	45
NB_N_021	1	3.4	0	0	n/a	18.7	67.5
NB_N_022	100	4.7	0	0	n/a	28.0	67.5
NB_N_023	1	3.4	0	0	n/a	18.7	90
NB_N_024	100	4.7	0	0	n/a	28.0	90
NB_N_025	1	3.4	0	0	n/a	18.7	135
NB_N_026	100	4.7	0	0	n/a	28.0	135
NB_N_027	1	3.4	0	0	n/a	20.1	292.5
NB_N_028	100	4.7	0	0	n/a	25.7	292.5
NB_N_029	1	3.4	0	0	n/a	20.1	337.5
NB_N_030	100	4.7	0	0	n/a	25.7	337.5

*Water levels shown reflect highest values applied, i.e. as boundary condition input to coarse resolution (regional) models.

3.5 Results of Wave Transformation Modelling – Nearshore Extreme Waves

The following sub-sections summarize the results of the 1 year and 100 year return period SWAN model simulations. Colour contour plots are provided to show examples of how wave parameters are transformed in nearshore areas of New Brunswick, resulting in different levels of exposure to storm wave conditions across the 14 identified coastal flood hazard zones. Wave parameters were also extracted from the models at 16 point locations in the Southern Region and 26 locations in the Northern Region, to quantitatively summarize variations in wave exposure along the coast, and to provide the basis for wave run-up evaluations (Section 4).

3.5.1 Southern Region

An example of significant wave height ($H_s \approx H_{m0}$) contours output from the combined SWAN models for the Southern Region is shown in Figure 29[3] for the 1 in 100 year return period and offshore waves from the south-westerly direction (Simulation ID: NB_S_016). Vector arrows from the coarse grid model are overlaid on the significant wave height contour map to illustrate the peak wave direction. Of the four coastal flood hazard zones in this region, Grand Manan Island in Zone 11 and Zone 12 are exposed to the highest waves propagating from the Atlantic Ocean. The mainland in Zone 11 is relatively sheltered from offshore waves by the Fundy Islands. Of the four zones in this region, the coast of Zone 14 (Westmorland County - Rockport to Sackville) has the least exposure to storm waves propagating from the Atlantic Ocean.

Nearshore extreme wave conditions in the Southern Region corresponding to maximum significant wave heights and associated sea state parameters from all SWAN production simulations are provided in Appendix B, for both the 1 in 1 year and 1 in 100 year return periods.

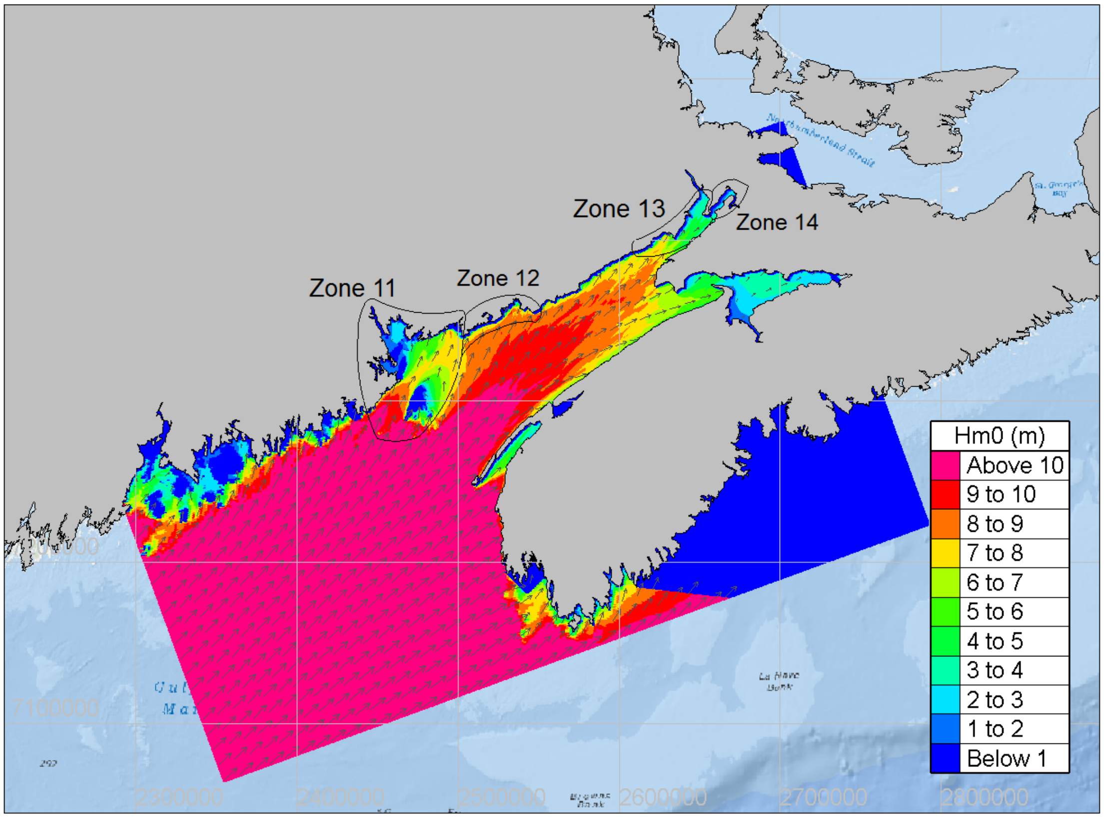

Figure 29. Modelled significant wave heights in the Southern Region for 1 in 100 year return period offshore wave conditions from the southwest (225°).

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[3] Note that areas east of Nova Scotia where H_{m0} is indicated as less than 1 (shown blue in Figure 29) represent output from deactivated grid cells – refer to the explanation in Section 3.2.3.

Sea state parameters associated with 1 and 100 year return period conditions are summarized for 16 points along the southern New Brunswick coast (Figure 30) in Table 9. The points were selected to reflect the observed variability in wave conditions within coastal flood hazard zones and in sufficient water depths to reflect conditions seaward of areas of significant wave breaking. To illustrate the point numbering system, 11-1 is the first extraction point in Zone 11, 13-2 is the second extraction point in Zone 13, and so on. For each return period, the summary table provides sea state parameters corresponding to the highest significant wave heights resulting from the modelling scenarios listed in Table 7. The summary indicates that coastal hazard Zone 11 is exposed to the highest waves in the Southern Region for both the 1 and 100 year return period conditions. Storm significant wave heights in the southern New Brunswick nearshore are generally dominated by waves propagating into the Bay of Fundy from the Atlantic Ocean, except in some areas north and northwest of Grand Manan Island (Zone 11) and at the head of the Bay of Fundy (Zones 13 and 14), where winds blowing over the Bay of Fundy cause the highest waves. The nearshore sea state parameters listed in Table 9 will be used in conjunction with topographic-bathymetric data and shoreline type as the basis for evaluating wave run-up at different locations along the New Brunswick coast in Phase 3.

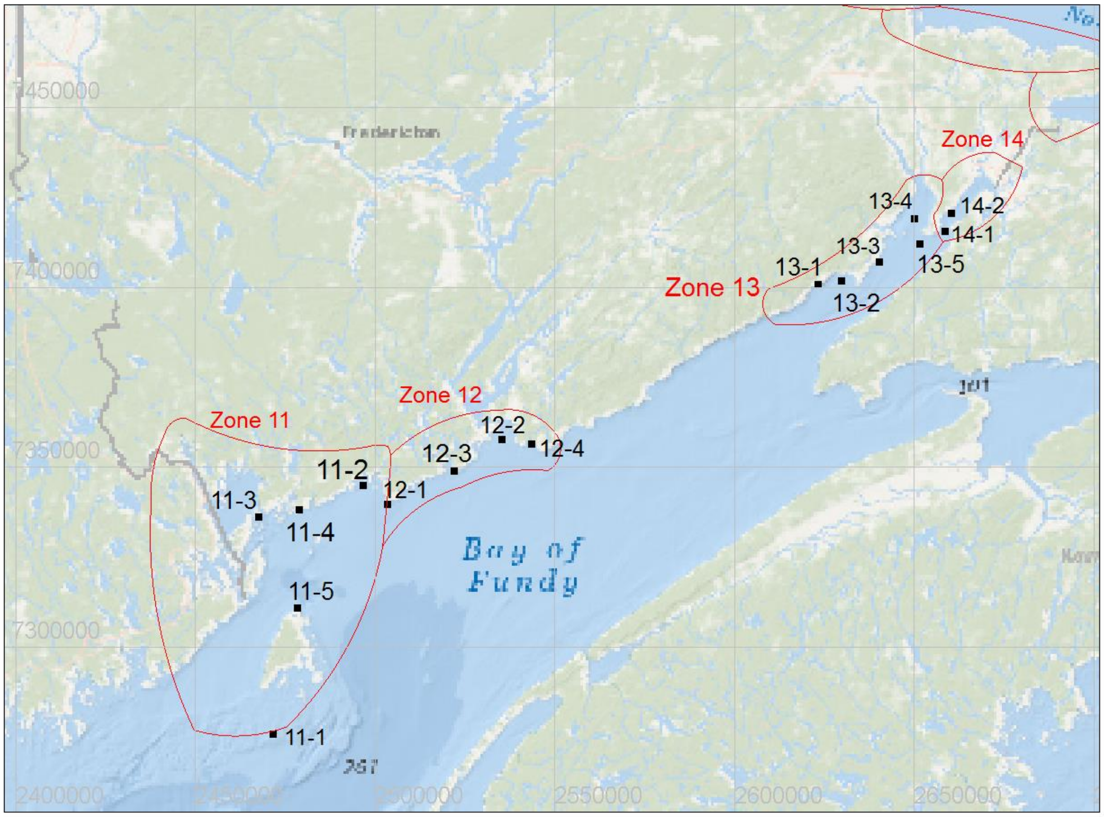


Figure 30. Locations in the Southern Region where summary results were extracted from the SWAN model.

Table 9. Summary of wave conditions at extraction points in the Southern Region.

Point	Co-ordinates		Return Period (years)	Water Depth (m)	Nearshore Wave Conditions		
	Easting (m)	Northing (m)			H_{m0} (m)	T_p (s)	θ_p (°)
11-1	2471723	7275762	1	35	4.6	11	186
			100	36	12.4	15	199
11-2	2496810	7344805	1	22	3.3	11	185
			100	23	8.3	15	186
11-3	2467700	7336197	1	24	1.7	7	110
			100	24	3.0	9	107
11-4	2478798	7338266	1	31	2.7	11	175
			100	31	5.7	13	182
11-5	2478495	7310896	1	26	2.6	7	57
			100	27	5.9	11	64
12-1	2503351	7339534	1	23	3.3	11	178
			100	23	8.5	15	173
12-2	2535296	7357658	1	23	2.9	11	190
			100	24	8.0	15	193
12-3	2522122	7348851	1	20	3.1	11	187
			100	21	8.1	15	185
12-4	2543521	7356518	1	23	3.0	11	200
			100	23	8.1	15	203
13-1	2623326	7400812	1	26	1.9	6	196
			100	26	5.3	14	197
13-2	2629769	7401702	1	25	2.4	7	211
			100	25	6.5	11	210
13-3	2640168	7407167	1	24	1.6	5	202
			100	25	4.0	10	207
13-4	2650039	7419022	1	25	1.5	5	202
			100	26	3.5	7	210
13-5	2651570	7411956	1	25	1.7	6	225
			100	25	4.1	9	230
14-1	2658531	7415602	1	25	1.5	7	229
			100	25	3.7	8	233
14-2	2660288	7420473	1	25	1.0	4	212
			100	26	2.3	6	214

3.5.2 Northern Region

An example of significant wave height ($H_s \approx H_{m0}$) contours output from the combined SWAN models for the Northern Region is shown in Figure 31 for 1 in 100 year return period waves from the east-northeast (NB_N_008). Of the ten coastal flood hazard zones in this region, Zones 4 to 7 are exposed to the highest waves propagating from the Gulf of Saint Lawrence. Zones in Chaleur Bay (Zones 1 to 3) are relatively sheltered from offshore waves by the Acadia Peninsula. Zones in the Northumberland Strait (Zones 8 to 10) are relatively sheltered from offshore waves by Prince Edward Island.

Nearshore extreme wave conditions in the Northern Region corresponding to maximum significant wave heights and associated sea state parameters from all SWAN production simulations are provided in Appendix B, for both the 1 in 1 year and 1 in 100 year return periods.

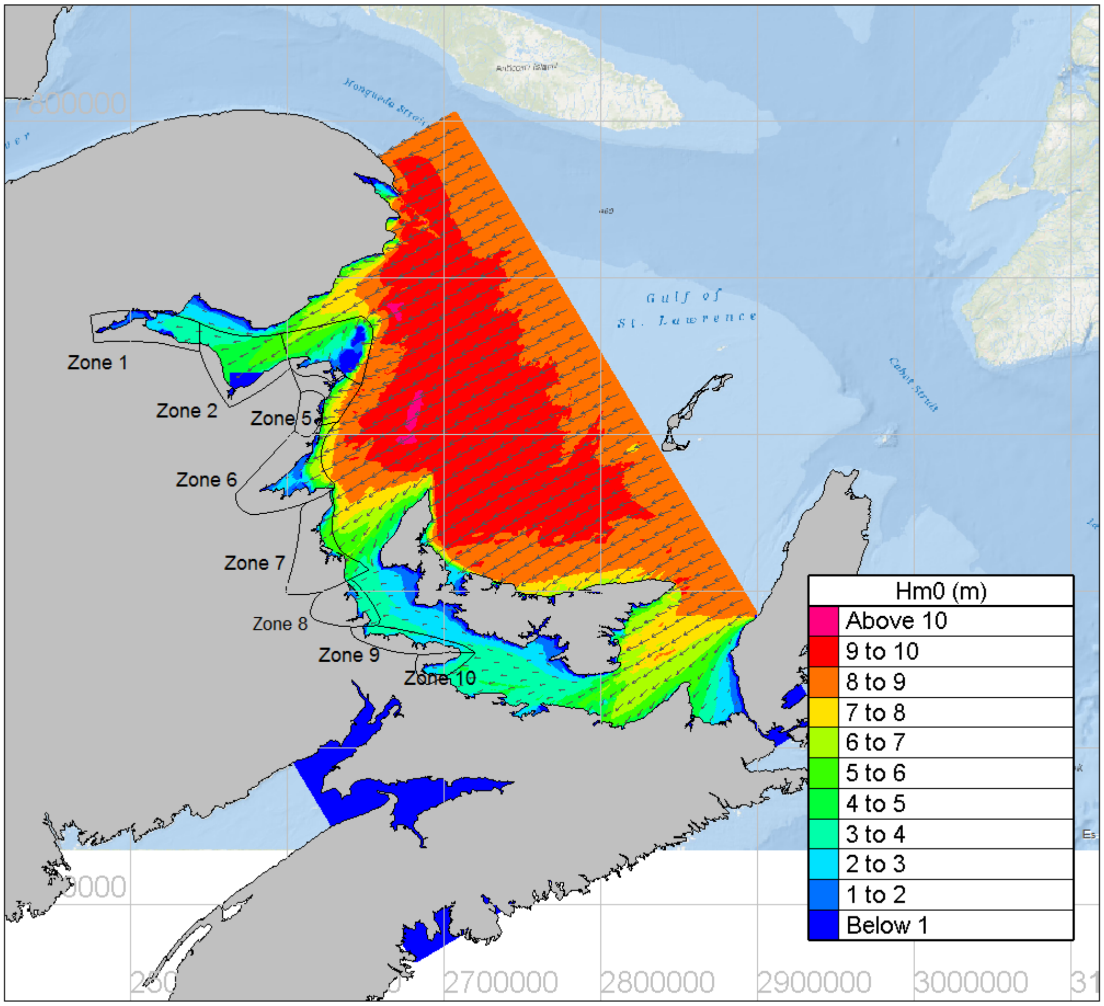


Figure 31. Modelled significant wave heights in the Northern Region for 1 in 100 year return period offshore wave conditions from the east-northeast (67.5°).

Sea state parameters associated with 1 and 100 year return period conditions are summarized for 26 points along the northern New Brunswick coast (Figure 32) in Table 10. For each return period, the summary table provides sea state parameters corresponding to the highest significant wave heights resulting from the modelling scenarios listed in Table 8. The summary indicates that coastal hazard Zones 3-7 are exposed to the highest storm waves in the Northern Region, corresponding to waves propagating towards New Brunswick from the Gulf of Saint Lawrence. In Zones 1, 2, 9 and 10, the highest waves are generated by winds blowing over local fetches in Chaleur Bay and Northumberland Strait.

Table 10. Summary of wave conditions at extraction points in the Northern Region.

Point	Co-ordinates Easting (m)	Co-ordinates Northing (m)	Return Period (years)	Water Depth (m)	Nearshore Wave Conditions* H_{m0} (m)	Nearshore Wave Conditions* T_p (s)	Nearshore Wave Conditions* θ_p (°)
1-1	2523195	7671536	1	21	2.3	6	92
			100	22	3.9	8	88
1-2	2536642	7661949	1	19	2.4	6	74
			100	20	3.9	8	71
2-1	2553123	7656332	1	19	2.8	7	83
			100	20	4.8	9	79
2-2	2559976	7646778	1	19	2.9	7	69
			100	20	5.2	9	69
2-3	2564608	7636065	1	19	2.8	10	56
			100	20	5.1	10	53
2-4	2584392	7640794	1	21	2.7	6	336
			100	22	3.8	11	29
2-5	2595588	7647260	1	20	2.8	6	294
			100	21	4.2	10	32
3-1	2605239	7650155	1	21	2.6	7	295
			100	22	4.5	11	35
3-2	2628980	7655270	1	19	2.6	6	344
			100	20	3.9	13	17
3-3	2636990	7661737	1	11	2.8	6	287
			100	12	4.2	12	11
3-4	2652104	7651852	1	19	4.0	10	84
			100	20	7.7	13	87
3-5	2644402	7638871	1	19	3.9	9	100
			100	20	7.1	13	94
4-1	2631400	7623294	1	19	4.0	9	98
			100	20	6.8	11	100
4-2	2628043	7609303	1	18	4.1	9	92
			100	19	6.8	13	80
6-1	2625692	7599341	1	18	4.0	9	90
			100	19	6.6	11	89
6-2	2621775	7587141	1	18	3.9	9	87
			100	19	6.7	13	78
6-3	2628043	7571695	1	18	3.8	10	61
			100	19	6.8	13	56
7-1	2632374	7551609	1	19	3.4	9	65
			100	20	6.3	13	66
7-2	2629589	7536292	1	19	3.5	8	57
			100	21	6.0	13	58
7-3	2643513	7519584	1	19	3.2	8	7
			100	20	5.3	11	20
8-1	2649083	7508842	1	18	2.7	7	356
			100	19	4.0	8	121

8-2	2660818	7489349	1	19	2.8	7	350
			100	20	3.9	8	351
9-1	2676532	7477016	1	20	2.6	6	336
			100	21	4.0	7	88
9-2	2694633	7471646	1	19	2.5	6	304
			100	20	3.5	7	305
10-1	2718486	7459821	1	19	2.8	8	83
			100	20	4.1	8	99
10-2	2719967	7442970	1	18	3.1	9	71
			100	20	4.3	8	78

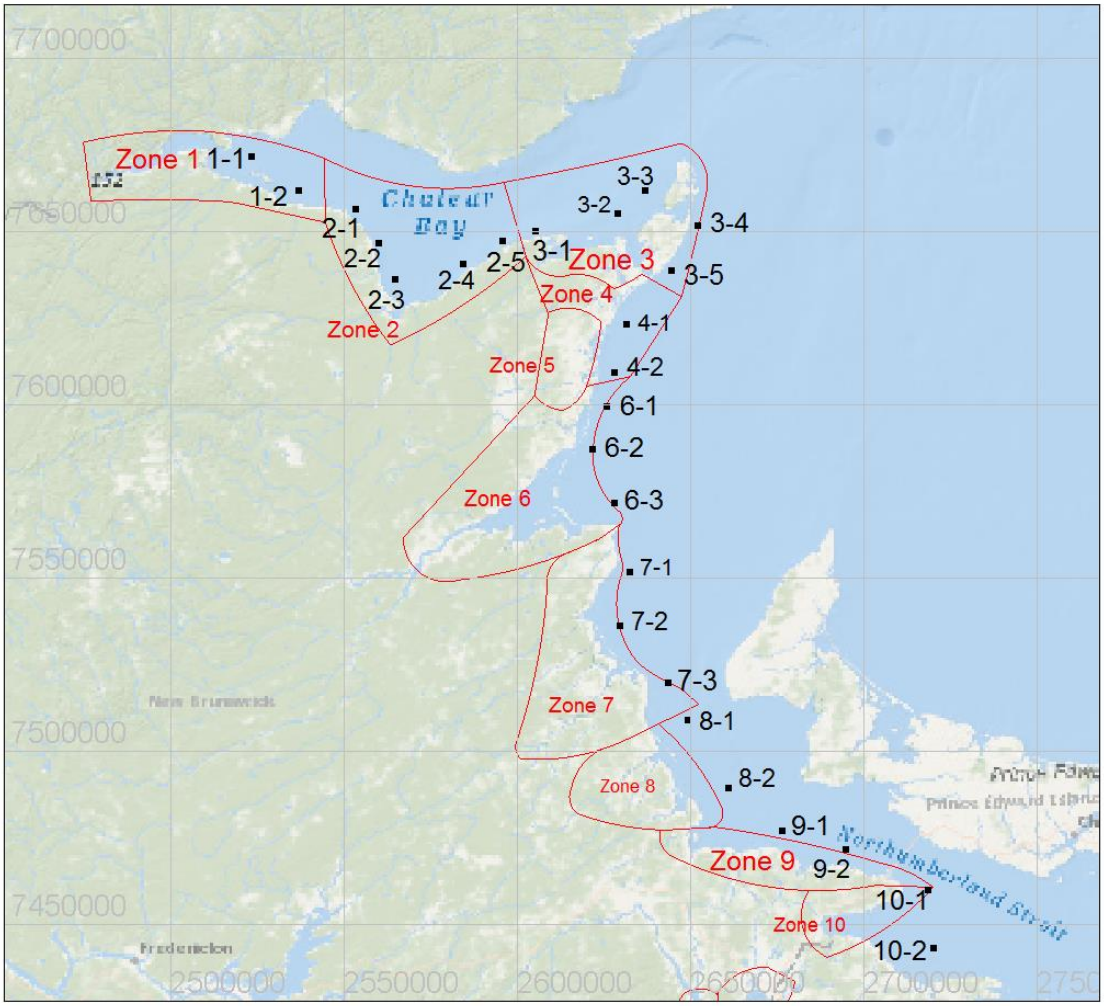


Figure 32. Locations in the Northern Region where summary results were extracted from the SWAN model.

3.5.3 Sensitivity tests

The differences in predicted significant wave heights in the Northern Region for 100 year return period offshore waves from the ENE, compared to results for the equivalent baseline simulation

(NB_N_008 in Table 8), are shown in Figure 33 to Figure 37 for adjusted model input parameters. Positive values indicate increases relative to the baseline simulation, and negative values indicate decreases.

Of the various model input parameters tested, results indicate that significant wave heights at the shoreline are most sensitive to wave breaking parameters (Figure 33 and Figure 34), with local changes as much as +0.3 m to -1.1 m from the baseline ($\gamma = 0.7$) for the range of breaker indexes investigated ($\gamma = 0.6$ to 0.73).

Application of the SWAN default bed friction coefficient ($c_{JON} = 0.038\ \mathrm{m^2s^{-3}}$) resulted in decreases in nearshore significant wave heights by as much as -0.4 m compared to the baseline scenario ($c_{JON} = 0.019\ \mathrm{m^2s^{-3}}$). However, the most significant changes in wave heights were seaward of the limit of depth-induced wave breaking (Figure 35), with depth-limited wave heights at the shoreline remaining similar to the baseline.

Decreases in applied water levels resulted in decreased nearshore significant wave heights relative to the baseline scenario (Figure 36 and Figure 37), by as much as -0.3 for zone-averaged water levels (as opposed to the zonal maxima applied in the baseline scenario), and -0.7 for 2010 water levels (as opposed to the 2100 water levels including sea level rise applied in the baseline scenario).

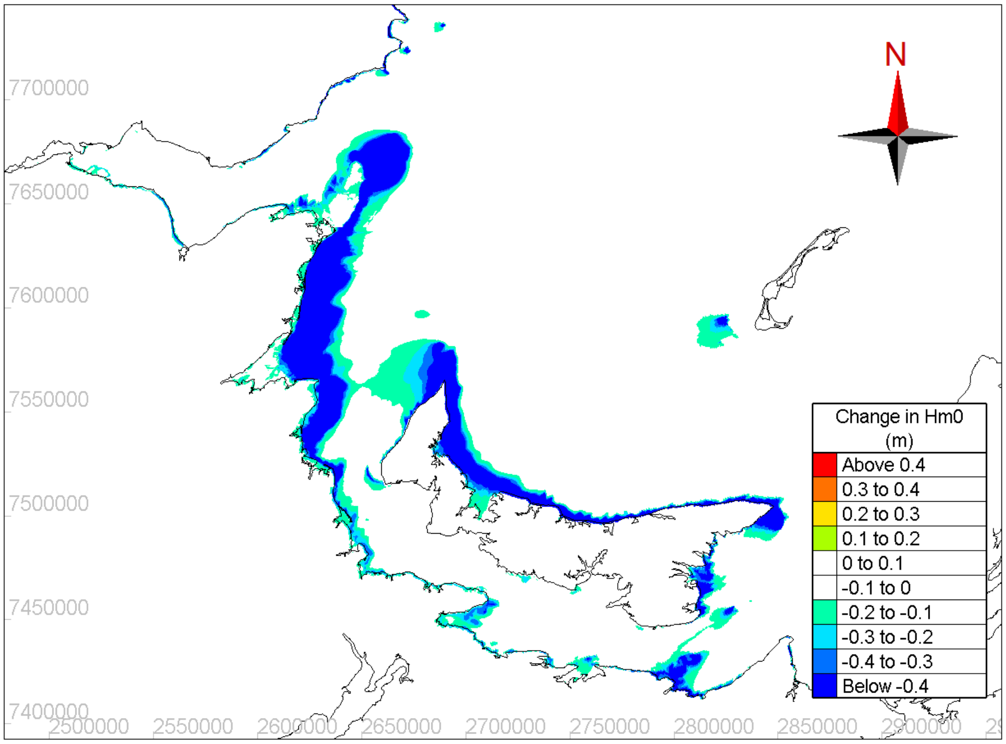


Figure 33. Difference in significant wave heights relative to baseline (NB_N_008) due to breaker index, γ = 0.6 (100 year return period offshore waves from ENE).

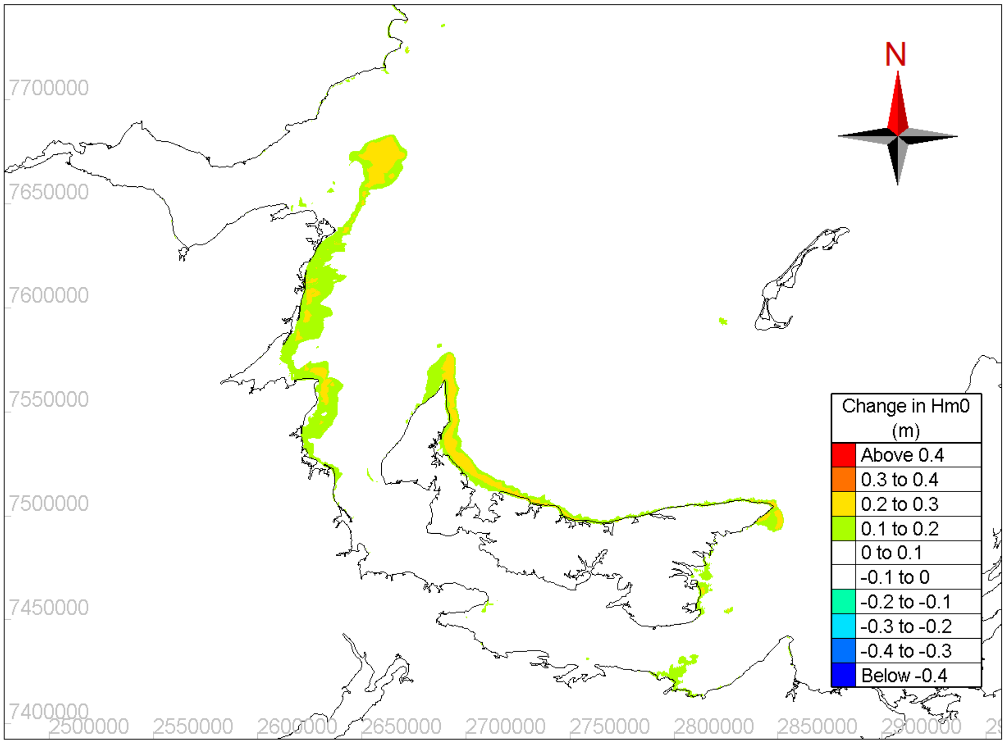


Figure 34. Difference in significant wave heights relative to baseline (NB_N_008) due to breaker index, γ = 0.73 (100 year return period offshore waves from ENE).

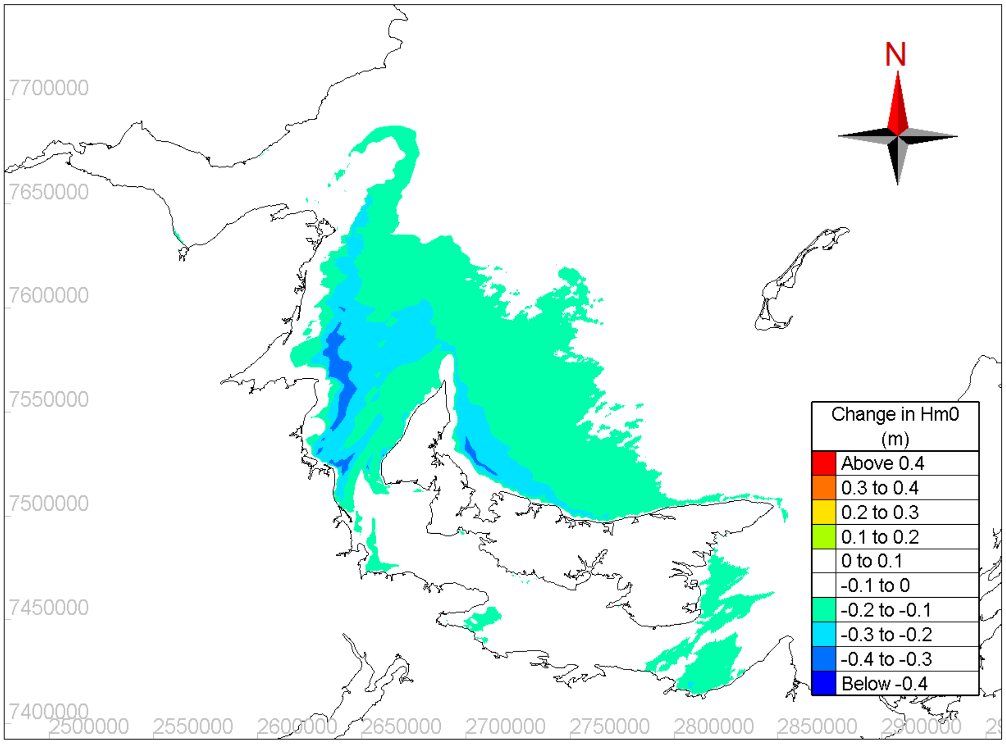


Figure 35. Difference in significant wave heights relative to baseline (NB_N_008) due to friction coefficient, c_{JON} = 0.038 m^2s^{-3} (100 year return period offshore waves from ENE).

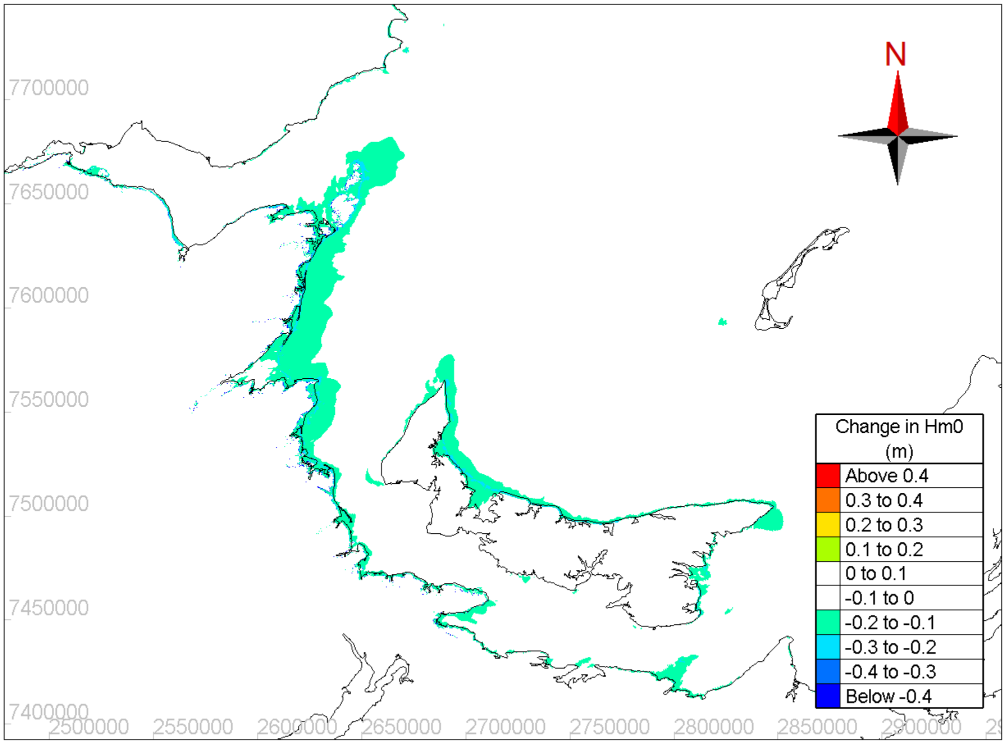


Figure 36. Difference in significant wave heights relative to baseline (NB_N_008) due to application of zonal average water levels (100 year return period offshore waves from ENE).

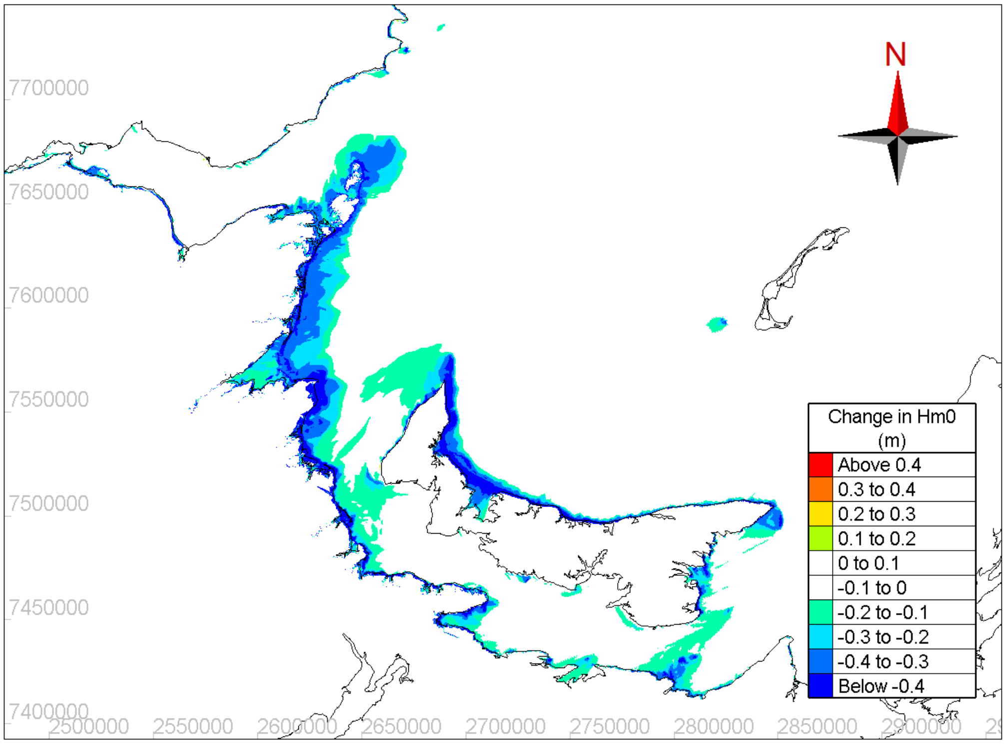


Figure 37. Difference in significant wave heights relative to baseline (NB_N_008) due to application of 2010 extreme water levels, i.e. excluding sea level rise to 2100 (100 year return period offshore waves from ENE).

4 Wave Run-Up

Output from the wave transformation study (Section 3) was used as the basis for evaluating extreme wave run-up heights (above the still water level) in each of the 14 coastal flood hazard zones. The following sub-sections describe the approach, inputs, methodology and results of the wave run-up analysis.

4.1 Definition of Wave Run-Up

Wave run-up, *R*, is defined as the maximum elevation of wave uprush on the shore above the still water level. Wave uprush consists of two components: the increase in mean water level due to wave action and breaking (setup), and fluctuations about that mean (swash).

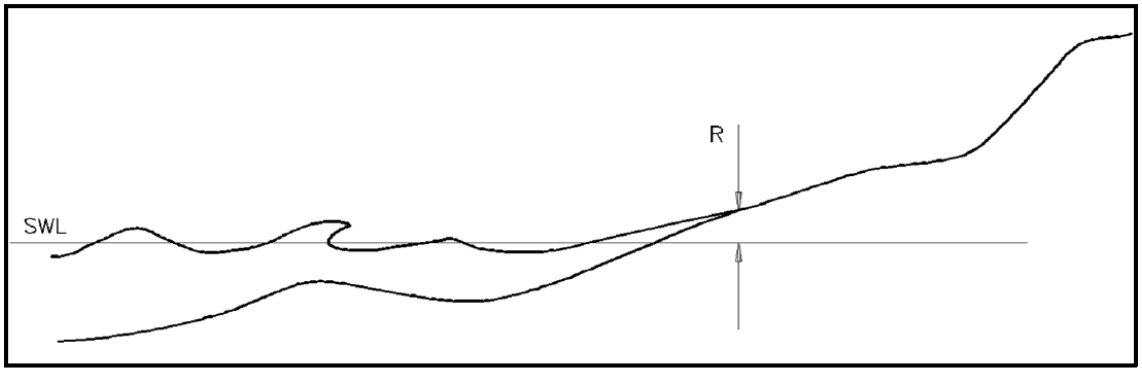


Figure 38. Definition sketch for wave run-up. Source: [19]

The limit of wave run-up depends principally on the following factors:

- Wave and water level conditions: the still water level, nearshore wave conditions (incident wave heights, steepness and breaking); and
- Shore characteristics: the type of feature at the shore (e.g. seawall, beach, cliff), including the cross-shore profile and slope, roughness and permeability.

If wave run-up levels are high enough, water will reach and pass over the crest of a shore-based feature (such as the top of a beach or seawall), a process referred to as wave overtopping. Wave run-up is an indicator of whether overtopping will occur but is not a useful indicator of hazards landward of the point of overtopping.

Various empirical formulae derived from physical model and field data are available to provide estimates of wave run-up on different types of coastal features (beaches, seawalls, etc.) [20] [19]. Wave run-up values are usually recorded (in the field or experiments) and expressed in terms of the “2%-value”, $R_{u2\%}$, which is the limit of run-up exceeded by 2% of the waves arriving at the shore in a given storm or sea state. The historical basis for this value is that if only 2% of waves reach the crest of a seawall or embankment during the design event, the crest or backslopes are unlikely to require armouring or other protection measures [20].

4.2 Methodology

The methodology for evaluating wave run-up involved two principal steps:

1. Classification of the New Brunswick shoreline to define wave run-up sub-zones (described in Section 4.2.1); and
2. Application of empirical wave run-up calculations to each sub-zone based on nearshore wave conditions and shoreline classification (Section 4.2.2).

4.2.1 Shoreline Classification

The 14 identified coastal flood hazard zones were sub-divided into wave run-up sub-zones, categorized based on slope (mean backshore slope within 200 m of the coast) and surficial material type (e.g. rock, sand and gravel, clay and silt). Geospatial information on backshore slope and materials along the coast was provided by the Geological Survey of Canada (G. Manson, personal communication, 13th August 2018) from the CanCoast database [21]. As the database only contains information on natural features and surficial geology, seawalls (rock, concrete or other) were not initially captured. Available satellite imagery was therefore used to visually identify extensive sections of seawall or rock armoured coast (exceeding approximately 100m in length). Where the presence of a seawall (or rock revetment) could not be confirmed based on available imagery but where other factors suggested the presence of such structures were highly likely (e.g. major roads running adjacent the coast), a seawall classification was assigned. Satellite imagery was also relied upon for for classifying the shoreline along Grand Manan Island, where CanCoast data coverage was not available. The resulting six shoreline classification types are listed in Table 11.

Table 11. Shoreline classification types.

Shoreline Classification Type	Backshore Slope	Material Type
Cliff / bluff	> 45°	Any
Mild-sloped beach	0° to 10°	Predominantly coarse sediments (sand / gravel)
Steep-sloped beach	10° to 45°	Predominantly coarse sediments (sand / gravel)
Mudflat / marsh	0° to 10°	Predominantly fine sediments (silt / clay)
Rock outcrop	0° to 45°	Rock
Seawall	N/A (visually identified)	

Sub-classification of the shoreline into the six categories listed in Table 11 resulted in a total of 614 sub-zones. Each sub-zone was assigned a unique numeric identifier according to the coastal flood hazard zone to which it belonged. An example of the sub-zones identified within Zone 12 is shown in Figure 39.

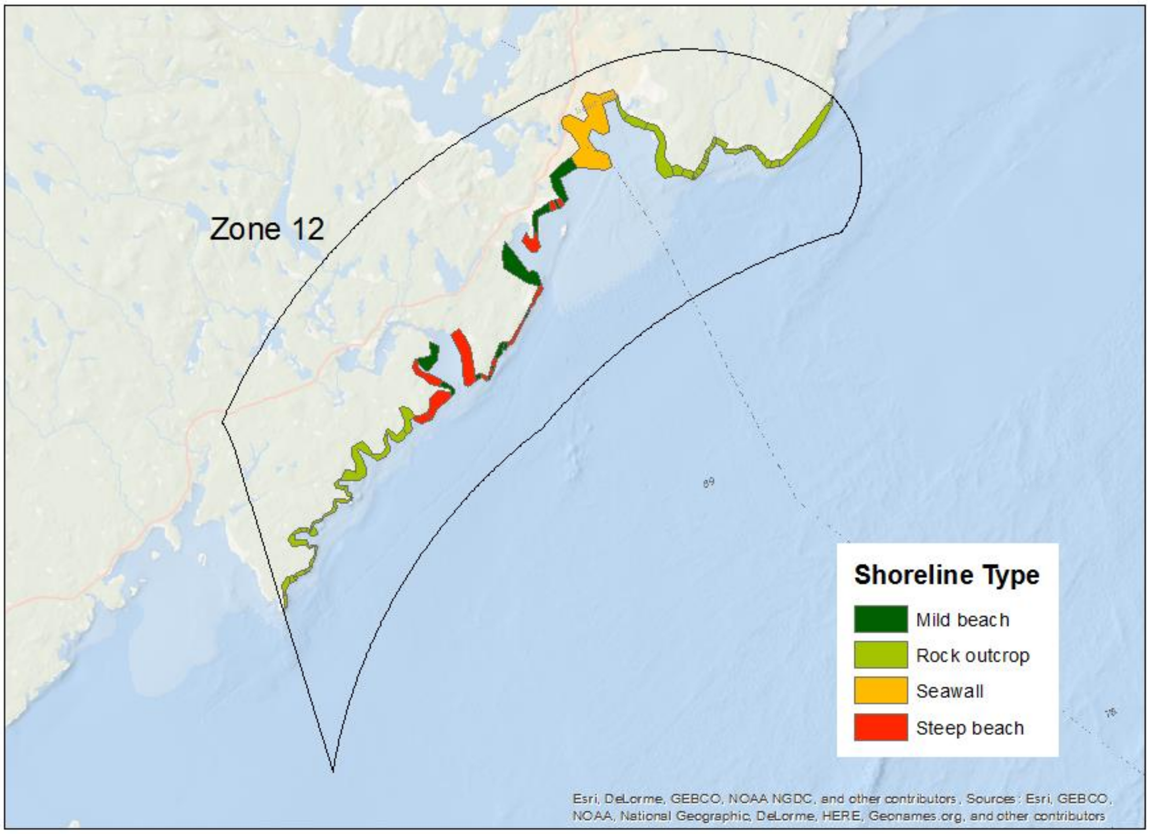


Figure 39. Sub-zones in Zone 12 (Saint John County – County Line to Cape Spencer).

4.2.2 Wave Run-Up Calculation Methods

For each sub-zone, wave run-up was estimated based on an appropriate empirical formula for each shoreline classification type (Table 12).

Table 12. Wave run-up formula adopted for each shoreline classification type.

Shoreline Classification Type	Wave Run-Up Formula
Cliff / bluff	EurOtop II manual [20], Eqn. 5.6
Mild-sloped beach	Coastal Engineering Manual [19], Mase (1989) formula, Eqn. II-4-29
Steep-sloped beach	EurOtop II manual, Eqn. 6.21
Mudflat / marsh	Coastal Engineering Manual, Mase (1989) formula, Eqn. II-4-29
Rock outcrop	EurOtop II manual, Eqns. 5.1 & 5.2
Seawall	EurOtop II manual, Eqn. 1.4

Most of the formulae express the wave run-up relative to the significant wave height at the toe of the coastal structure / feature, as a function of the breaker parameter (the ratio of the cross-shore slope to the wave steepness, which defines how the waves break on the shore). An example of this type of relationship is shown in Figure 40, plotted alongside measured data (primarily laboratory experiments). For large breaker parameters (i.e. steep slopes or low wave steepnesses), the run-up is insensitive to wave steepness and slope angle, and depends only on the wave height, reaching a maximum of around of around three times the significant wave height (i.e. $R_{u2\%} \approx 3H_{m0}$).

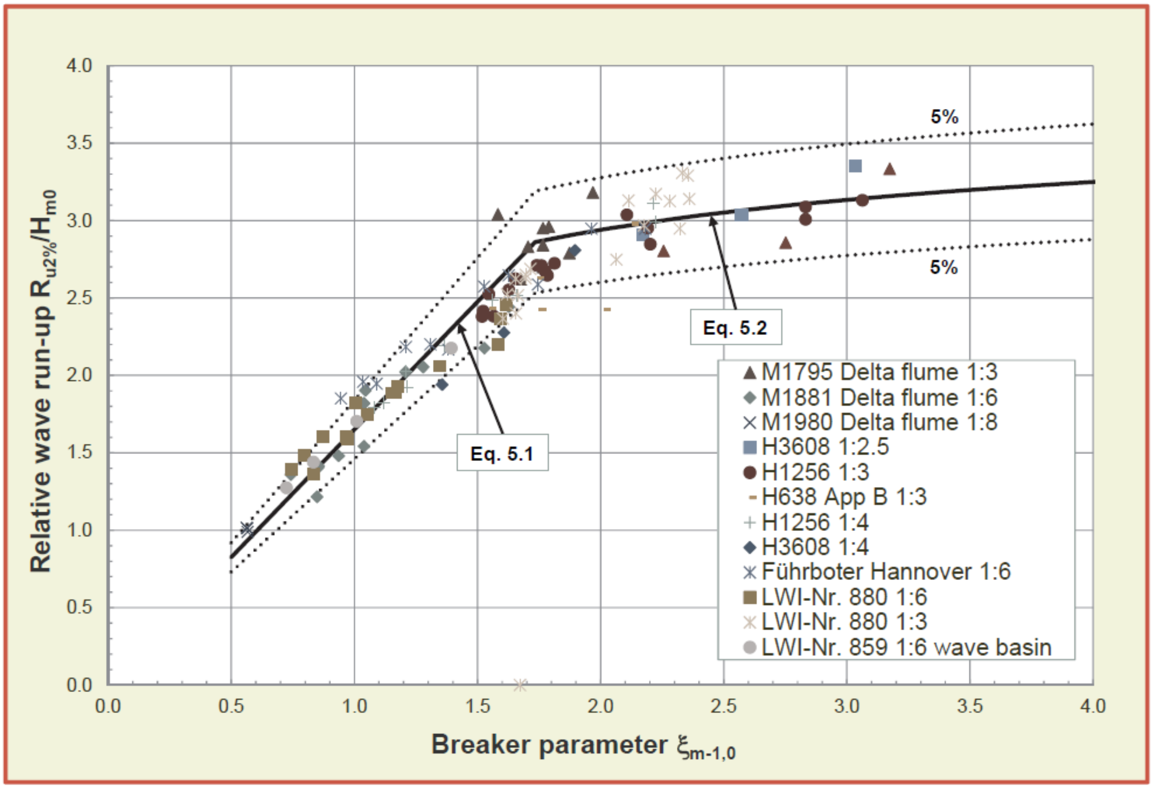


Figure 40. Wave run-up on relatively gentle, smooth and straight slopes. Source: [20]

For wave run-up formulae requiring wave conditions at the toe of the feature to be prescribed as input, the maximum significant wave heights (H_{m0}) and associated peak periods (T_p) for all SWAN model production runs were first evaluated throughout the model domain. Input wave parameters to the wave run-up formulae were then based on sub-zonal averages of values in the SWAN model grid cells closest to the shore.

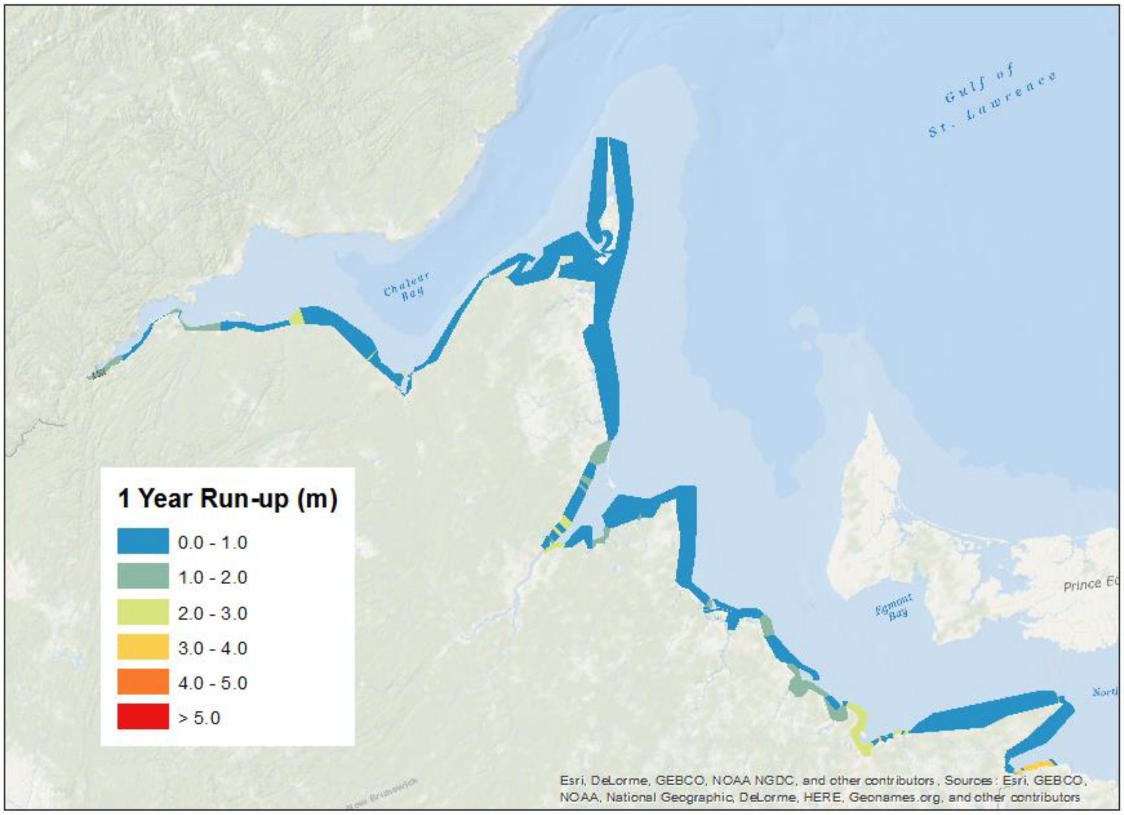
For wave run-up formulae requiring “deep water” wave conditions to be prescribed as input (e.g. Mase, 1989), the procedure described above was first followed, before reverse-shoaling the wave conditions to the deep water limit for use in the run-up formulae.

Calculated wave run-up heights for each sub-zone were expressed in terms of 2% run-up limits ($R_{u2\%}$).

4.3 Results of Wave Run-up Analysis

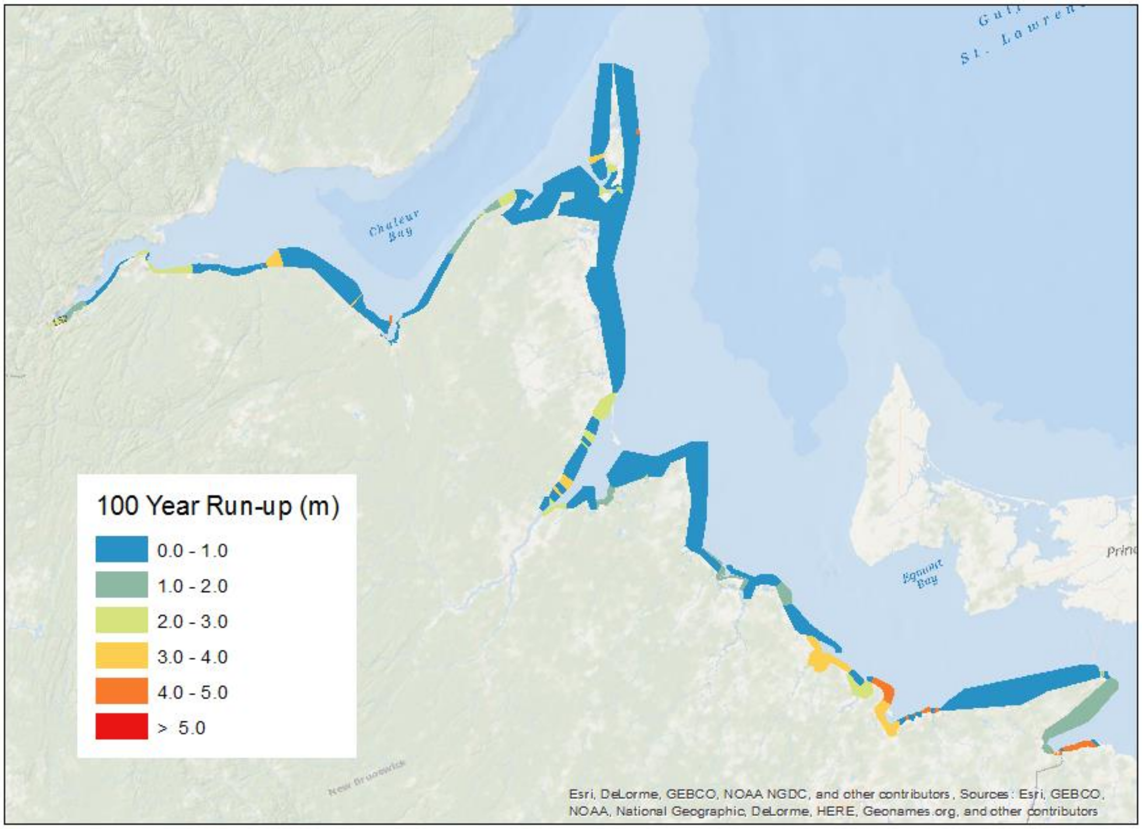
Calculated wave run-up heights for each sub-zone in the Northern Region are shown graphically in Figure 41 for the 1 in 1 year return period and Figure 42 for the 1 in 100 year return period condition. Wave run-up heights in the Southern Region are shown in Figure 43 and Figure 44. The results illustrate the dependence of wave run-up heights not only on wave exposure, but also the shore type / profile. In most wave run-up formulae (Table 12), wave run-up heights are directly proportional to the cross-shore slope, so values tend to be much higher for steep-sloped seawalls, cliffs and rock outcrops. In these locations, calculated wave run-up heights (based on the assumption of an infinitely long slope) may exceed the crest height of the seawall, cliff or rock outcrop, resulting in wave overtopping discharges. In such cases, wave run-up is not a useful indicator of the hazard level (see explanation in Section 4.4).

Wave run-up heights ($R_{u2\%}$ values for the 1 year and 100 year return periods) for each sub-zone polygon are provided in shapefile format in Appendix C.



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 41. Calculated 1 year return period wave run-up heights ($R_{u2\%}$) in the Northern Region.



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 42. Calculated 100 year return period wave run-up heights ($R_{u2\%}$) in the Northern Region.

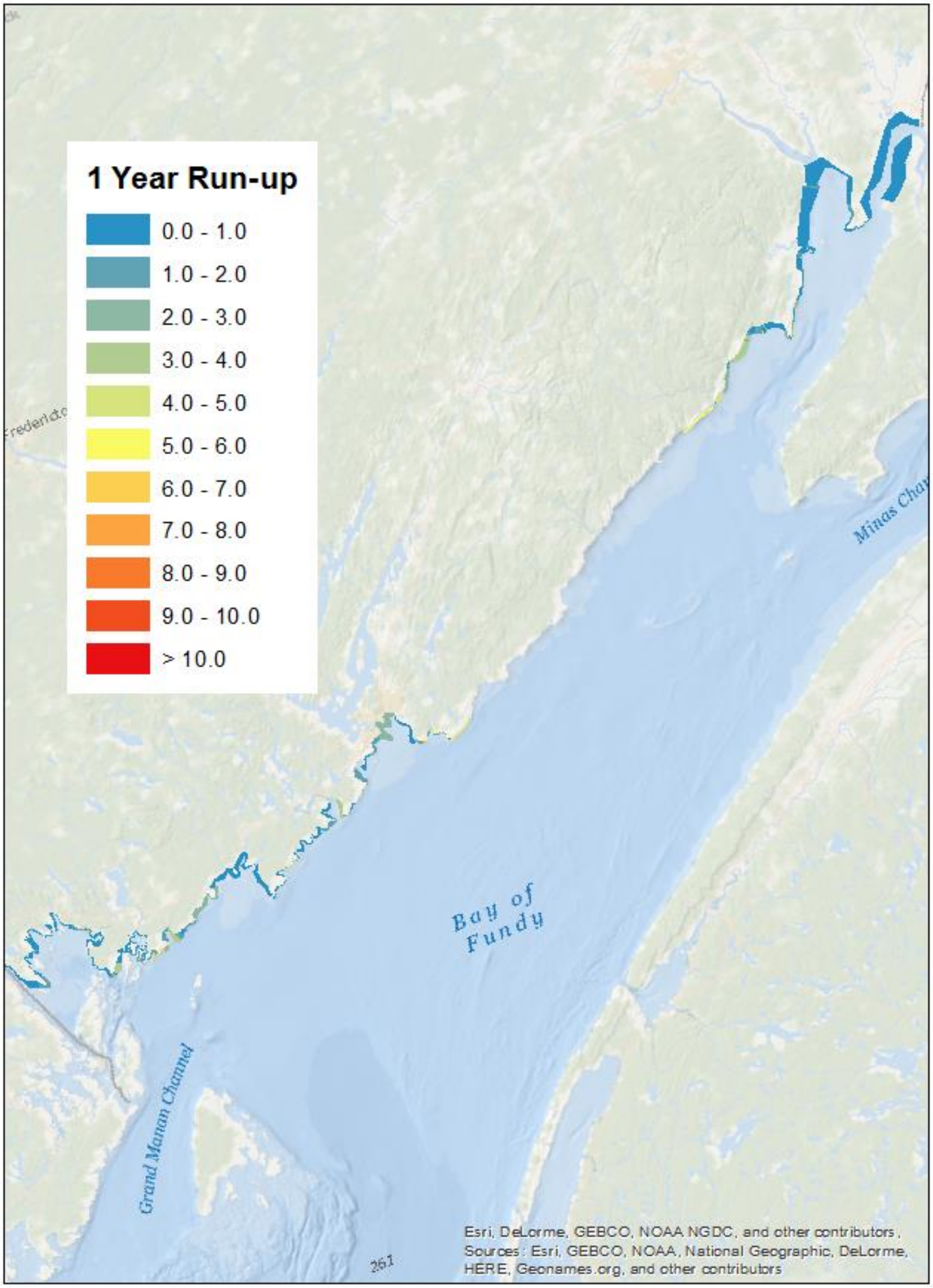
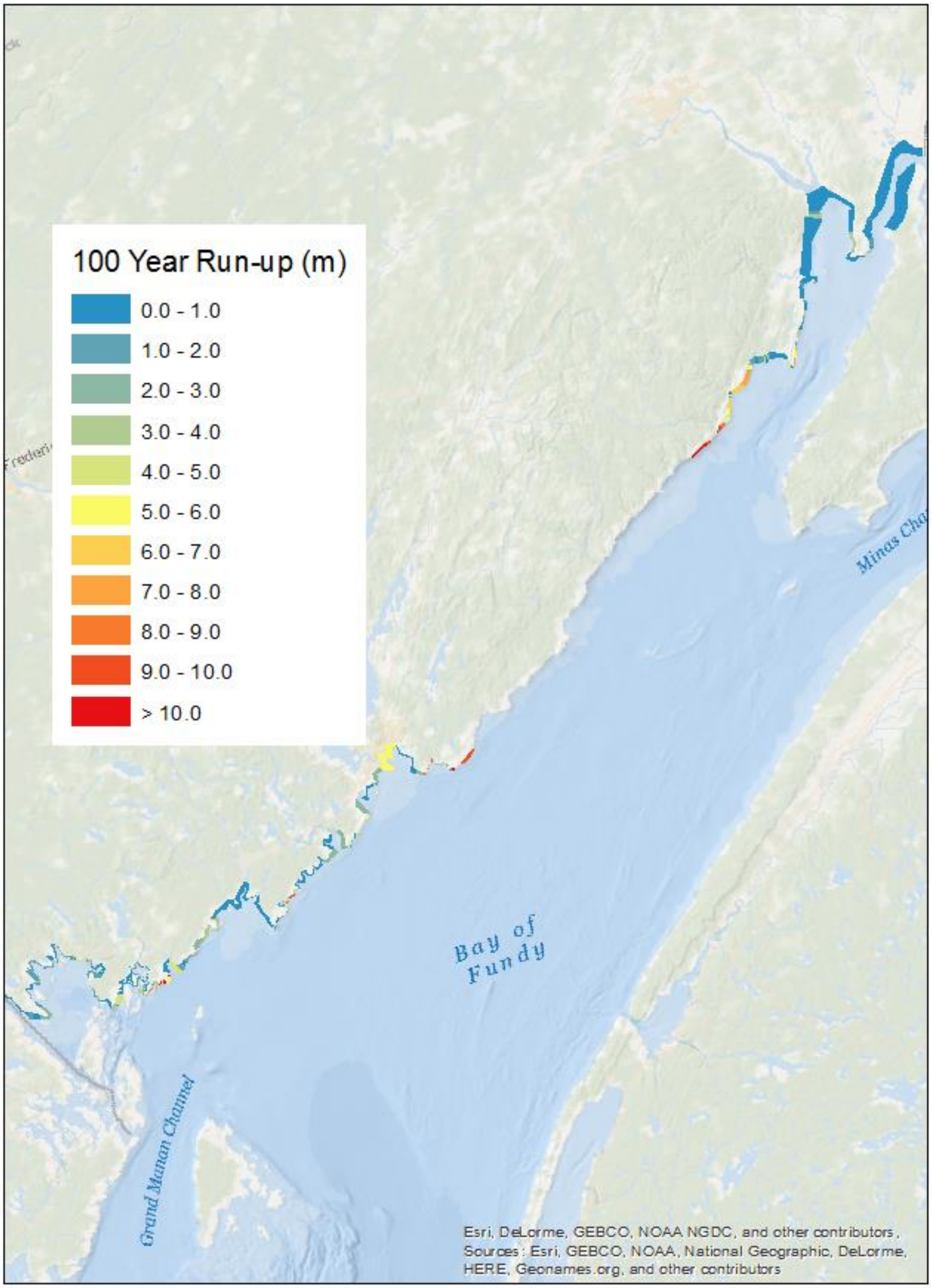


Figure 43. Calculated 1 year return period wave run-up heights ($R_{u2\%}$) in the Southern Region.



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 44. Calculated 100 year return period wave run-up heights ($R_{u2\%}$) in the Southern Region.

4.4 Limitations and Uncertainty

The extreme wave run-up heights developed and presented in this report are regional estimates, based on nearshore extreme wave conditions and shore types (slope and physical features) characteristic of each identified sub-zone. They represent wave run-up heights associated with the predominant shore type in each sub-zone. Localized differences in shore conditions and/or the presence of structures may result in actual wave run-up values that are higher or lower than the estimates. In addition, where run-up heights exceed the crest height of structures or dikes, wave overtopping discharge will occur.

To illustrate the potential uncertainty associated with variability within sub-zones, site-specific wave run-up heights were evaluated for two randomly selected locations (one in the Northern Region and one in the Southern Region, shown as red lines in Figure 45 and Figure 46) and compared to run-up heights evaluated for the encompassing sub-zones based on the methodology described in Section 4.2. The comparisons are shown in Table 13, and indicate relative errors in the range 11-26% for sub-zone averages compared to the site-specific estimates.

Figure 45. Location in the Northern Region (within Sub-Zone 9_9) where wave run-up was evaluated.

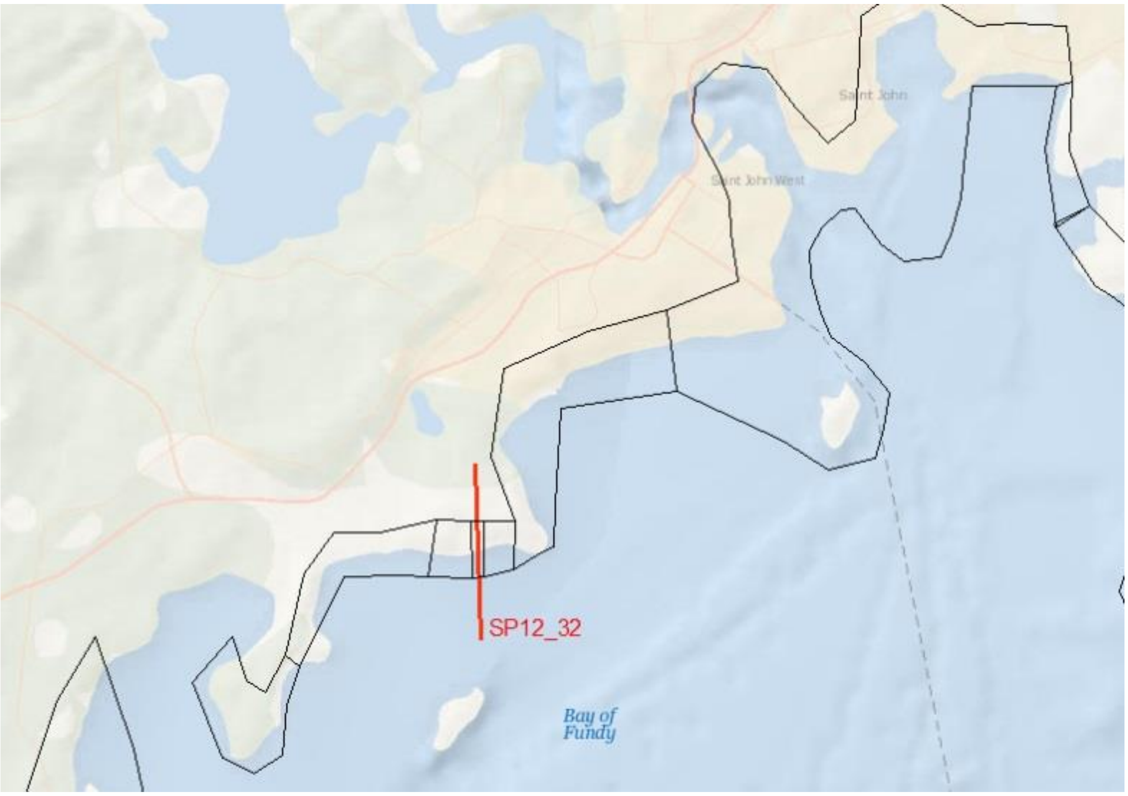


Figure 46. Location in the Southern Region (within Sub-Zone 12_32) where wave run-up was evaluated.

Table 13. Comparison of wave run up heights evaluated using site-specific and sub-zone averaged inputs.

Return Period	Northern Region (Sub-Zone 9_9)			Southern Region (Sub-Zone 12_32)		
	$R_{u2\%}$ (Site Specific)	$R_{u2\%}$ (Sub-Zone Average)	Relative Error	$R_{u2\%}$ (Site Specific)	$R_{u2\%}$ (Sub-Zone Average)	Relative Error
1	0.34	0.40	18%	1.79	2.11	18%
100	0.46	0.58	26%	2.86	3.18	11%

The wave run-up estimates in Section 4.3 were calculated based on inputs derived from numerical model predictions of nearshore wave conditions under prescribed extreme water level conditions, including relative sea level rise to the year 2100. Wave run-up elevations associated with lower water levels will likely be reduced, including as a result of increased wave energy dissipation in nearshore areas due to shallower water depths. Uncertainty surrounding future sea level rise rates also has direct implications for the wave run-up estimates.

All methods of estimating wave run-up have inherent uncertainties. The empirical formulae used for this study are typically used for preliminary assessments or conceptual design of coastal structures. More accurate estimates of wave run-up and/or overtopping require the application of numerical or physical modelling to site-specific conditions, or calibration of formulae using local field measurements.

As explained in Section 4.1, wave uprush on the shore includes two components: the increase in mean water level due to wave action and breaking (setup), and fluctuations about that mean (swash). Wave set-up is implicitly reproduced in the physical model tests on which the wave run-up equations are based, but only over the length of foreshore reproduced in the model. There is, in general, no requirement to add on an additional water level increase for wave set-up when calculating overtopping discharges using the methods discussed in this report [20]. However, wave set-up may be underestimated in places where the foreshore is very long and gently-sloping. Refining estimates of wave set-up would require dedicated wave models to be developed for such areas, and/or measurements in the surf zone.

The wave run-up estimates presented here are based on static topographic/bathymetric information. During intense storm events, significant seabed deformation, erosion, breaching of beaches and shore protection structures (such as seawalls), and other morphological changes can occur, altering the incident wave conditions and wave run-up/overtopping performance. Such effects were not considered and would require detailed morphological modelling and/or analysis to address. Similarly, long-term changes in shoreline position due to human interventions and/or geomorphological processes were not considered.

The potential impacts of climate change on extreme winds and associated sea state conditions have not been considered.

5 Data Visualization Options Appraisal

A review of options for presentation and visualization of the outputs from this study was carried out in collaboration with NBDELG. The primary objective was to provide technical advice to NBDELG on the development of a geospatial visualization tool to effectively communicate the data associated with the Coastal Flood Hazard Mapping project to the public and others. The work towards this objective involved a meeting in Fredericton (13 June 2018) and several teleconferences (10 and 12 July 2018) with NBDELG's project team and in-house specialists to review and discuss needs, existing capabilities and the format of data deliverables.

The following sub-sections describe NRC's review of map-based web application technology options presented to NBDELG to inform the discussion, the identified needs and recommended approach to data visualization, and the agreed format of data deliverables to meet NBDELG's data visualization needs.

5.1 Overview of Web Mapping Applications

The emergence of web mapping platforms such as ArcGIS Online, OpenGeo, Leaflet, Mapbox and others have greatly increased possibilities for sharing and communication of geospatial data. These platforms allow users to create, develop and share maps through the internet. Ease-of-development and customization capabilities vary amongst different platforms. A comparison of two approaches to web mapping application development is provided in Table 14.

Table 14. Comparison of cloud- and web-based platforms for map-based applications

Cloud Platforms (e.g. ArcGIS Online, Mapbox Studio, CartoDB, Open Geo Suite)	**Web Development** (e.g.. Mapbox, Leaflet, OpenLayers)
Description: Cloud platforms such as ArcGIS Online, Mapbox Studio, CartoDB, OpenGeo Suite (and numerous others) rely on existing, relatively user-friendly, infrastructure that allows users to upload data and create maps using web application builders. **Advantages** • Intuitive what-you-see-is-what-you-get application • Allows development of web apps without writing code • Imports shapefiles and other standard GIS file formats • Enables rapid app development	**Description:** This approach is similar to developing a web site from scratch, without relying on existing platforms, allowing for greater flexibility but requiring technical knowhow. Mapping services / capabilities are facilitated by web development platforms such as Mapbox, Leaflet, OpenLayer, Google api will only provide the mapping services. **Advantages** • Customization is limitless in terms of style, analysis and tools • No constraints in terms of analysis or viewing • Applications can range from relatively simple to extremely complex • Open-source libraries widely available

• Hosting included • Examples and tutorials widely available	to guide/help development
Disadvantages	**Disadvantages**
• Membership / software licensing costs (typically several thousand dollars per year) • Customization is limited • Options are constrained to the platform features and technology • Typically useful for viewing only. Any type of analysis (e.g. statistical analysis of data) can be slow and expensive	• Web coding capabilities are required • Development can be more time consuming depending on the complexity of the application • Requires hosting to store the application and data

5.2 Data Visualization Needs

During the meetings and teleconferences attended by NRC and NBDELG staff, needs and requirements for visualization of the study output were discussed. The topics covered by the discussions included:

- Existing data and formats associated with the Coastal Flood Hazard Mapping project;
- Technologies and platforms currently held or used by NBDELG;
- Stakeholder audiences and key messages / information to be communicated / emphasized;
- Level of interactivity and automation desired;
- Desired aesthetic quality of communication tools;
- Needs for integration with existing NBDELG systems (ArcGIS Online); and
- NBDELG’s desired level of development / maintenance effort.

As outcomes of the discussions, the following principles were agreed with respect to requirements for data visualization:

- Data visualization should focus on continued development and enhancement of the existing NBDELG system, which is under development in ArcGIS Online. It was agreed that creating a separate application for wave run-up could confuse users (mainly the public).
- With respect to communicating output from the wave run-up study, it was agree that the application should show information from two layers, as follows:
    - “Wave Run-Up Height”. A polygon-based layer containing information on the wave run-up sub-zone number, shoreline classification type, and wave run-up heights for the 1 year and 100 year return periods (based on the highest waves from all scenarios investigated for each return period). It was agreed that the methodology used to calculate the wave run-up height should be clearly explained using figures and/or language suitable for communication to a non-technical audience, which will be made accessible to users via the application (e.g. via bubbles or web links).
    - “Extreme Wave Conditions”. Raster or grid-based layers showing significant wave heights and peak wave periods for the 1 year and 100 year return periods. A

non-technical summary explanation of the basis for the wave conditions should be provided, for incorporation in the application.

5.3 Data Deliverables

The following sub-sections describe the data deliverables, provided in Appendices to this report.

5.3.1 Wave Run-Up Height

The “Wave Run-Up Height” file is a polygon-based GIS layer (shapefile). The polygons are based on the wave run-up sub-zones developed using methods discussed in Section 4.2.1. The layer contains properties as shown in Table 15.

Table 15. Properties of “Wave Run-Up Height” layers.

Properties	Units	Description
Zone Number	-	Coastal flood hazard zone identifying number, as specified by NBDELG [3], indicating the zone in which each wave run-up sub-zone lies
Sub-zone number	-	Unique wave run-rup sub-zone identifier (unique to each subzone)
Shoreline Type	-	Descriptive shoreline classification type applicable to each sub-zone (e.g. cliff/bluff, seawall, etc.)
Ru2%_1yr	m	2% wave run-up height above still water level for the 1 year return period
Ru2%_100yr	m	2% wave run-up height above still water level for the 1 year return period

5.3.2 Extreme Wave Conditions

The “Extreme Wave Conditions” files consist of gridded output from each of the fine spatial resolution (100m) nearshore wave model grids described in Section 3.2.1. Each file contains four (space-delimited) columns of data, as described in Table 16.

Table 16. Properties of “Extreme Wave Conditions” layers.

Column Header	Units	Description
Xp	m	Easting grid co-ordinate in New Brunswick co-ordinate system (EPSG: 2953)
Yp	m	Easting grid co-ordinate in New Brunswick co-ordinate system (EPSG: 2953)
Depth	m	Water depth (i.e. water level elevation minus bathymetry elevation)
Hm0	m	Significant wave height (maximum value for all runs associated with each return period)
Tp	s	Peak wave period (value associated with maximum Hm0 for each return period)
PWD	°, “from”, measured clockwise from true north	Peak wave direction (value associated with maximum Hm0 for each return period)

Values corresponding to land-based grid points are indicated by values of Depth = -99.00, Hm0 and Tp = -9.00, and PWD =-999.0.

5.3.3 Explanatory (Summary) Text for Users

Suggested summary text for inclusion in the web-based data visualization application (e.g. as pop-up bubbles) is presented in Table 17. The text and embedded links are specific to each shoreline classification type.

Table 17. Suggested explanatory text for public users.

Cliff / bluff	Wave run-up heights are indicative of the vertical height of wave uprush on the shore above the still water level (including tides, storm surges, sea level rise). The heights are expressed as "2% values", meaning they represent the limit of wave run-up exceeded by 2% of the waves arriving at the shore in a storm. Wave run-up heights are representative of typical or predominant nearshore extreme wave conditions, backshore slopes and shore type (i.e. cliff / bluff) in this sub-zone. Localized differences in shore conditions and/or the presence of structures may result in actual wave run-up values that are higher or lower than the estimates. Where run-up heights exceed the crest height of the cliff / bluff or coastal structures, wave overtopping will occur. The wave run-up heights correspond to extreme wave and water level events, including allowances for relative sea level rise to the year 2100. Wave run-up heights will generally be reduced for lower water level events or conditions. The wave run-up heights are based on the assumption of a static / stable shoreline, and do not reflect shoreline / bathymetric changes that can occur during storm events, long-term morphological changes, or the future impacts of human interventions on the coast. Wave run-up in this sub-zone was calculated based on equation 5.6 of the EurOtop II manual (http://www.overtopping-manual.com/docs/EurOtop%20II%202016%20Pre-release%20October%202016.pdf). For further details of the wave run-up calculation methodology, please refer to NRC Technical Report OCRE-TR-2018-026.
Mild-sloped beach	Wave run-up heights are indicative of the vertical height of wave uprush on the shore above the still water level (including tides, storm surges, sea level rise). The heights are expressed as "2% values", meaning they represent the limit of wave run-up exceeded by 2% of the waves arriving at the shore in a storm. Wave run-up heights are representative of typical or predominant nearshore extreme wave conditions, backshore slopes and shore type (i.e. beach) in this sub-zone. Localized differences in shore conditions and/or the presence of structures may result in actual wave run-up values that are higher or lower than the estimates. Where run-up heights exceed the crest height of the beach/dune or coastal structures, wave overtopping will occur. The wave run-up heights correspond to extreme wave and water level events, including allowances for relative sea level rise to the year 2100. Wave run-up heights will generally be reduced for lower water level events or conditions. The wave run-up heights are based on the assumption of a static / stable shoreline, and do not reflect shoreline / bathymetric changes that can occur during storm events, long-term morphological changes, or the future impacts of human interventions on the coast. Wave run-up in this sub-zone was calculated based on equation II-4-29 of the Coastal Engineering Manual (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/636F617374616C20656E67696E656572696E67206D616E75616C/) For further details of the wave run-up calculation methodology, please refer to NRC Technical Report OCRE-TR-2018-026.

Steep-sloped beach	Wave run-up heights are indicative of the vertical height of wave uprush on the shore above the still water level (including tides, storm surges, sea level rise). The heights are expressed as "2% values", meaning they represent the limit of wave run-up exceeded by 2% of the waves arriving at the shore in a storm. Wave run-up heights are representative of typical or predominant nearshore extreme wave conditions, backshore slopes and shore type (i.e. beach) in this sub-zone. Localized differences in shore conditions and/or the presence of structures may result in actual wave run-up values that are higher or lower than the estimates. Where run-up heights exceed the crest height of the beach/dune or coastal structures, wave overtopping will occur. The wave run-up heights correspond to extreme wave and water level events, including allowances for relative sea level rise to the year 2100. Wave run-up heights will generally be reduced for lower water level events or conditions. The wave run-up heights are based on the assumption of a static / stable shoreline, and do not reflect shoreline / bathymetric changes that can occur during storm events, long-term morphological changes, or the future impacts of human interventions on the coast. Wave run-up in this sub-zone was calculated based on equation 6.21 of the EurOtop II manual (http://www.overtopping-manual.com/docs/EurOtop%20II%202016%20Pre-release%20October%202016.pdf). For further details of the wave run-up calculation methodology, please refer to NRC Technical Report OCRE-TR-2018-026.
Mudflat / marsh	Wave run-up heights are indicative of the vertical height of wave uprush on the shore above the still water level (including tides, storm surges, sea level rise). The heights are expressed as "2% values", meaning they represent the limit of wave run-up exceeded by 2% of the waves arriving at the shore in a storm. Wave run-up heights are representative of typical or predominant nearshore extreme wave conditions, backshore slopes and shore type (i.e. mudflat / marsh) in this sub-zone. Localized differences in shore conditions and/or the presence of structures may result in actual wave run-up values that are higher or lower than the estimates. Where run-up heights exceed the crest height of the marsh or coastal structures, wave overtopping will occur. The wave run-up heights correspond to extreme wave and water level events, including allowances for relative sea level rise to the year 2100. Wave run-up heights will generally be reduced for lower water level events or conditions. The wave run-up heights are based on the assumption of a static / stable shoreline, and do not reflect shoreline / bathymetric changes that can occur during storm events, long-term morphological changes, or the future impacts of human interventions on the coast. Wave run-up in this sub-zone was calculated based on equation II-4-29 of the Coastal Engineering Manual (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/636F617374616C20656E67696E656572696E67206D616E75616C/) For further details of the wave run-up calculation methodology, please refer to NRC Technical Report OCRE-TR-2018-026.

Rock outcrop	Wave run-up heights are indicative of the vertical height of wave uprush on the shore above the still water level (including tides, storm surges, sea level rise). The heights are expressed as “2% values”, meaning they represent the limit of wave run-up exceeded by 2% of the waves arriving at the shore in a storm. Wave run-up heights are representative of typical or predominant nearshore extreme wave conditions, backshore slopes and shore type (i.e. rocky shores) in this sub-zone. Localized differences in shore conditions and/or the presence of structures may result in actual wave run-up values that are higher or lower than the estimates. Where run-up heights exceed the crest height of the rock outcrop or coastal structures, wave overtopping will occur. The wave run-up heights correspond to extreme wave and water level events, including allowances for relative sea level rise to the year 2100. Wave run-up heights will generally be reduced for lower water level events or conditions. The wave run-up heights are based on the assumption of a static / stable shoreline, and do not reflect shoreline / bathymetric changes that can occur during storm events, long-term morphological changes, or the future impacts of human interventions on the coast. Wave run-up in this sub-zone was calculated based on equations 5.1 and 5.2 of the EurOtop II manual (http://www.overtopping-manual.com/docs/EurOtop%20II%202016%20Pre-release%20October%202016.pdf). For further details of the wave run-up calculation methodology, please refer to NRC Technical Report OCRE-TR-2018-026.
Seawall	Wave run-up heights are indicative of the vertical height of wave uprush on the shore above the still water level (including tides, storm surges, sea level rise). The heights are expressed as “2% values”, meaning they represent the limit of wave run-up exceeded by 2% of the waves arriving at the shore in a storm. Wave run-up heights are representative of typical or predominant nearshore extreme wave conditions and shore type (i.e. seawalls) in this sub-zone. Typical rock slopes of 1:2 (vertical:horizontal) were assumed. Localized differences in shore/structure conditions and/or the presence of structures may result in actual wave run-up values that are higher or lower than the estimates. Where run-up heights exceed the crest height of the seawall, wave overtopping will occur. The wave run-up heights correspond to extreme wave and water level events, including allowances for relative sea level rise to the year 2100. Wave run-up heights will generally be reduced for lower water level events or conditions. The wave run-up heights are based on the assumption of a static / stable shoreline, and do not reflect shoreline / bathymetric changes that can occur during storm events, long-term morphological changes, or the future impacts of human interventions on the coast. Wave run-up in this sub-zone was calculated based on equation 1.4 of the EurOtop II manual (http://www.overtopping-manual.com/docs/EurOtop%20II%202016%20Pre-release%20October%202016.pdf). For further details of the wave run-up calculation methodology, please refer to NRC Technical Report OCRE-TR-2018-026.

6 Summary and Conclusion

Regional extreme wave run-up estimates were developed for identified sub-zones within 14 coastal flood hazard zones in the province of New Brunswick. The study methodology involved a statistical analysis of available long-term offshore wind and wave hindcast data, numerical modelling to transform extreme wave conditions to the nearshore, and the application of empirical formulae to calculate wave run-up heights. The primary outputs from the study consisted of:

- Gridded nearshore extreme wave conditions (maximum significant wave heights and associated peak wave periods) corresponding to 1 year and 100 year return period offshore wind/wave conditions in combination with 2100 extreme water levels;
- Representative wave run-up heights (corresponding to 2% wave run-up heights above still water levels) in 614 sub-zones, corresponding to the same events/return periods described above; and
- Suggested explanatory (summary) text for incorporation in NBDELG's data visualization tool.

The outputs are provided in GIS-compatible formats in Appendix B and C. The formats of the data deliverables were determined based on a review of needs to support web-based data visualization and communication of the study findings to a public audience. Recommendations included a continued focus on the development and enhancement of NBDELG's existing ArcGIS Online-based web mapping application.

Explanatory text detailing the key assumptions, limitations and uncertainty associated with the study methods and outputs is provided within this report, for cross-referencing by the web-based application as appropriate.

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Appendix A

Offshore Extreme Wave Analysis

Appendix B
Nearshore Extreme Wave Data

Appendix C

Wave Run-Up Height Data