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WAVE RUN-UP CONTRIBUTIONS TO COASTAL FLOOD HAZARDS IN NEW BRUNSWICK

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Abstract: New Brunswick's coastal communities and civil engineering systems are vulnerable to flooding associated with tides, extreme storm surges and wave events. Coastal flood hazards and risks are projected to increase over time, as a consequence of urbanization and climate change effects. The province's Coastal Flood Hazard Mapping project aims to develop new maps for approximately 2,270 linear kilometers of the New Brunswick coast. A regional wave run-up study was conducted to characterize storm wave contributions to coastal flood hazards. Representative extreme wave run-up heights were evaluated for 614 zones along the New Brunswick coast. Zones were identified and classified according to extreme water level characteristics, wave exposure, shore type and gradient. The study involved statistical analyses of offshore wind and wave hindcast data, numerical wave transformation modelling to evaluate nearshore extreme wave conditions, and a systematic approach to calculating extreme wave run-up heights for each zone. Nearshore extreme wave parameters and run-up height data from the study will be incorporated in a publicly accessible, web-based map application, which will inform coastal flood risk management and climate change adaptation efforts in New Brunswick.

1 INTRODUCTION

Coastal flooding events occur regularly 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 (Zhai et al. 2015). Extreme sea level predictions are available for parts of the New Brunswick coast (Environment Canada 2006). However, a complete set of coastal flood hazard maps based on a consistent mapping methodology does not yet exist. New Brunswick's Flood Risk Reduction Strategy (Government of New Brunswick 2014) and Climate Change Action Plan (Government of New Brunswick 2016) call for the renewal and expansion of the province's coastal and inland flood hazard maps, motivating the establishment of the Coastal Flood Hazard Mapping project. Under the Coastal Flood Hazard Mapping project, the province has funded studies to evaluate future extreme sea levels (R.J. Daigle Enviro 2017), including allowances for tides, extreme storm surges (atmospheric pressure setup and wind setup), and projected relative sea level rise to the year 2100. A set of 14 coastal flood hazard zones were identified, based on spatial variations in tides and storm surges (Figure 1). Wave-related contributions to the total extreme water levels (such as wave run-up) were excluded from this initial analysis. In this paper, we describe a regional wave run-up analysis, carried out to develop estimates of nearshore extreme (storm) waves and associated wave run-up heights for the 14 identified coastal flood hazard zones. The output from the study was used to inform coastal flood hazard mapping for the province and to support the development of a web-based data visualization tool, to facilitate improved public awareness of coastal flood hazards.

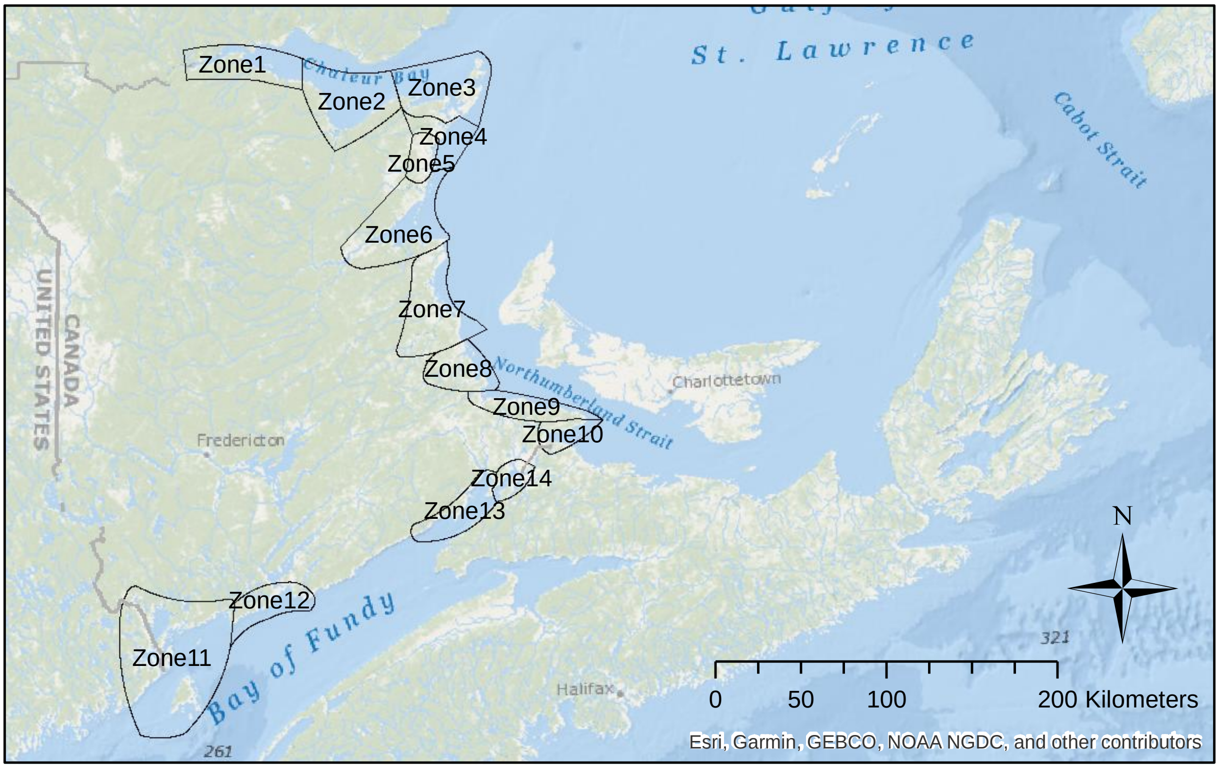

Figure 1: Coastal Flood Hazard Zones in New Brunswick

2 STUDY METHODOLOGY

2.1 Offshore Extreme Wind and Waves Analysis

A statistical analysis of extreme (storm) wind and wave conditions in New Brunswick offshore waters was conducted. The analysis relied on the Meteorological Service of Canada and Oceanweather (MSC50) hindcast dataset (Swail et al. 2006), which provides time series data on a 0.1°-resolution grid at hourly intervals for 21 wind and wave parameters, derived from a reanalysis of historical surface winds and waves off the east coast of Canada for the period 1954-2015. The approach to the offshore wind and wave analysis involved the following steps:

1. *Data preparation and homogenization.* Wind and wave time-series data were extracted from the MSC50 dataset at selected grid points, and sorted / analyzed to identify independent, identically distributed storm events. Sorting was based on wave/wind magnitudes and directions, 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), and fetch characteristics.
2. *Statistical analysis.* Extreme value (EV) analyses were performed on the storm peak significant wave heights and wind speeds using the Peaks-Over-Threshold (POT) method (e.g., Mazas & Hamm 2001) to evaluate return values associated return periods in the range 1 to 100 years.
3. *Evaluation of spectral wave parameters.* Parameters describing the wave spectra (i.e. peak wave periods, angular/directional spreading, spectral peakedness) representative of the assessed significant wave height return values were estimated using regression techniques.

The analysis was automated using Python-based scripts, referencing freely available libraries including NumPy (Oliphant 2006), WAFO (Brodtkorb et al. 2000) and Matplotlib (Hunter 2007), enabling rapid investigation and plotting of results for different grid points.

2.2 Regional Wave Transformation Modelling

Offshore extreme wave conditions in the Gulf of Saint Lawrence and the Gulf of Maine were transformed to the New Brunswick nearshore using SWAN (Cycle III version 41.20A), a third-generation numerical wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters (Booij et al. 1999; Ris et al. 1999). Nearshore wave conditions resulting from extreme winds blowing over local fetches were also investigated.

2.2.1 Wave Model Setup

Two systems of nested SWAN wave transformation models were set up; one covering the Bay of Fundy and extending offshore to the Gulf of Maine (referred to as the Southern Region – Figure 2), and one covering the Gulf of Saint Lawrence offshore region (Northern Region – Figure 3). The models were set up using an uncoupled nested approach, whereby a series of rectangular grids (300-500 m resolution) were used to generate boundary conditions for input to successively finer resolution (100 m) grids. The models incorporated topography and bathymetry data from various sources, including high resolution (1 m) LiDAR data covering much of the New Brunswick coast (Government of New Brunswick 2018), and multi-beam bathymetric survey data, obtained under license from the Canadian Hydrographic Service for the study. All elevation datasets were normalized to Canadian Geodetic Vertical Datum of 1928 (CGVD28) prior to incorporation in the models.

Offshore extreme wind and wave conditions from the MSC50 data analysis were used to drive the numerical models. 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). Spatially uniform water levels were input to the wave models based on return values given in R.J. Daigle Enviro (2017) for the 2100 time horizon, in combination with the corresponding wind/wave return period. This approach assumes a strong correlation between extreme wind/waves and water levels, in the absence of long-term, co-located and coincident water level, wind and wave data to support a joint probability analysis. JONSWAP-type wave spectra were specified at the offshore boundaries of the coarse resolution model grids. Stationary, uniform wind fields were applied based on the results of the offshore analyses. For simulations involving transformation of waves 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. Where the regressed wind speeds exceeded return values based on the extreme value analyses, the return values were applied as an upper bound for the return period. For simulations implemented to assess waves generated by local winds blowing over the model domains, wind speed return values were applied based on the extreme value analysis.

Bottom friction was activated in the SWAN model using the JONSWAP formulation (Delft University of Technology 2018a). For depth-induced wave breaking, the bore-based model of Battjes and Jansen (Delft University of Technology 2018b) was specified with a constant breaker index, $\gamma = 0.7$, based on values in the range 0.58 to 0.72 provided by three different breaker index models (Apostos et al. 2008; Battjes & Stive 1985; Goda 2010) . The phase-decoupled scheme for diffraction (Holthuijsen et al. 2003) 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). Triad wave interactions were activated to capture potentially important non-linear wave processes in shallow coastal waters.

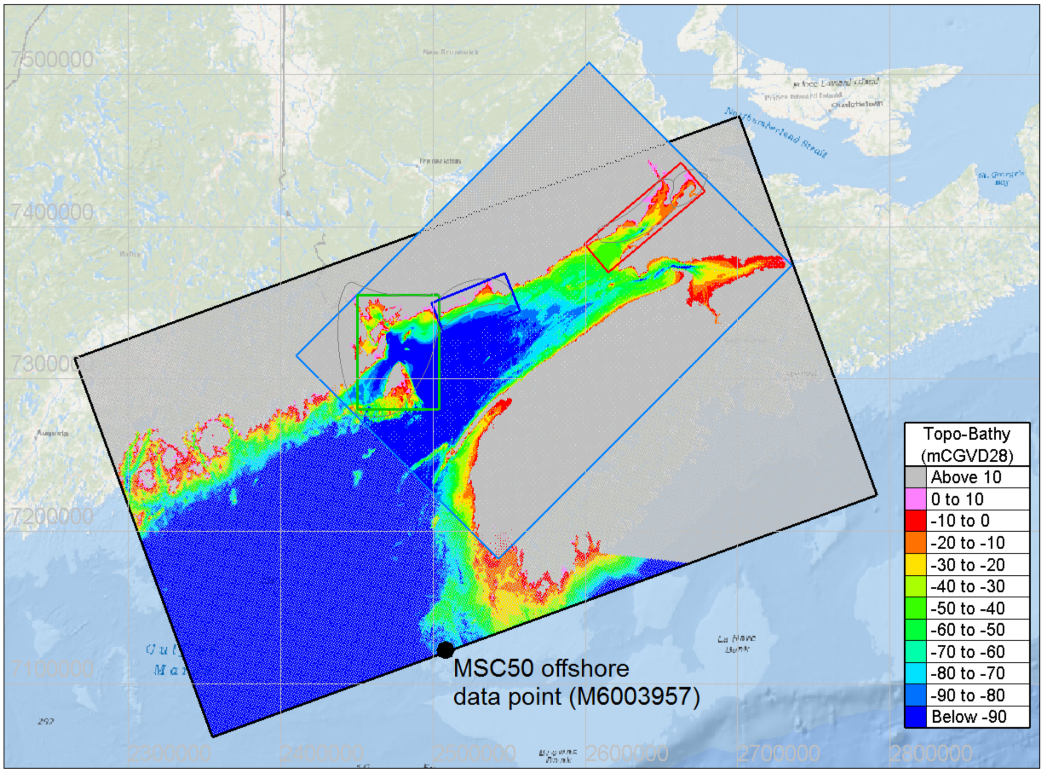

Figure 2: Southern Region SWAN model domain, nested sub-domains and bathymetry.

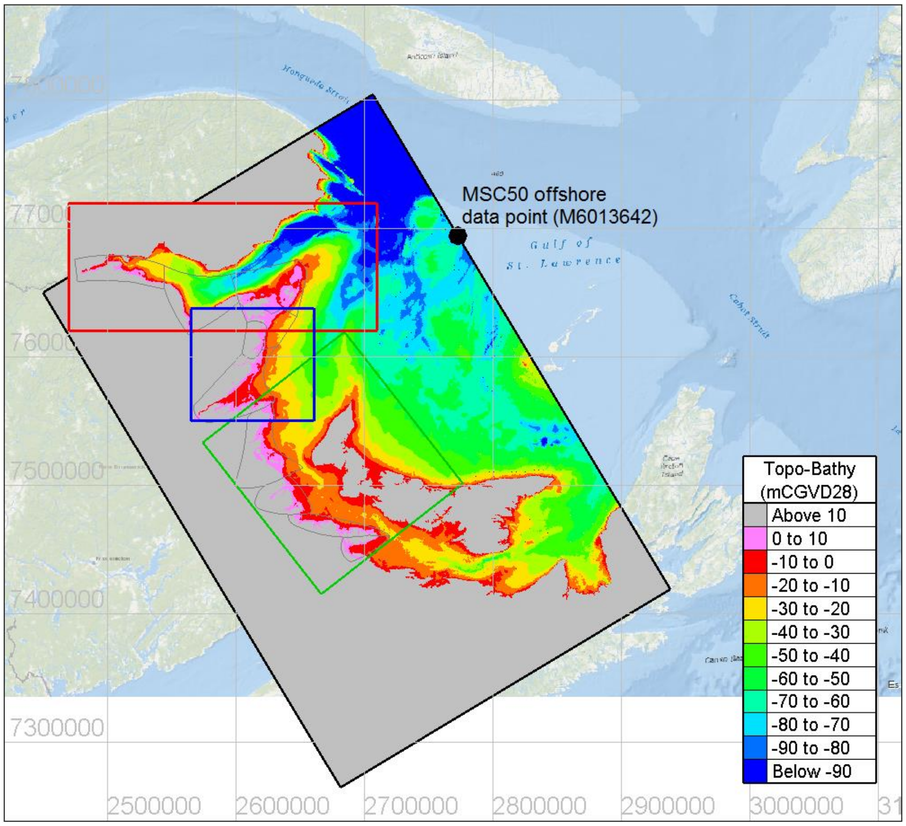

Figure 3: Northern Region SWAN model domain, nested sub-domains and bathymetry.

2.2.1 Wave Model Testing and Verification

Calibration of the SWAN models involved simulating a series of storms and comparing model output parameters (significant wave heights and peak wave periods) with available wave buoy data from Fisheries and Oceans Canada (MEDS) online archives. 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. For example, the friction coefficient, c_{JON}, was adjusted within the recommended range 0.019 m^2s^{-3} to 0.067m^2s^{-3}, with a value of 0.019m^2s^{-3} giving the closest agreement between modelled and measured storm peak significant wave heights. Following model calibration, 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). Example comparisons of measured and modelled storm significant wave heights at locations within the Southern Region (Point Lepreau) and Northern Region (Magdalen Shallows) are shown in Figure 4. The limited availability of wave buoy measurements placed constraints on the level of calibration / validation that could be achieved, and the model performance for specific storm events is strongly dependent on the quality of the offshore MSC50 data for the events. However, for storms where the MSC50 output is consistent with MEDS buoy data (e.g. the 1976 and 1995 events shown), the nested SWAN models, running in stationary mode, are capable of capturing peak storm significant wave heights in nearshore areas. Accepting that the MSC50 data is statistically representative over multi-decadal time scales, as demonstrated by Swail et al. (2006), there is some confidence that the models provide reasonable estimates of probabilistic (i.e. 1 year and 100 year return period) extreme wave conditions in nearshore areas.

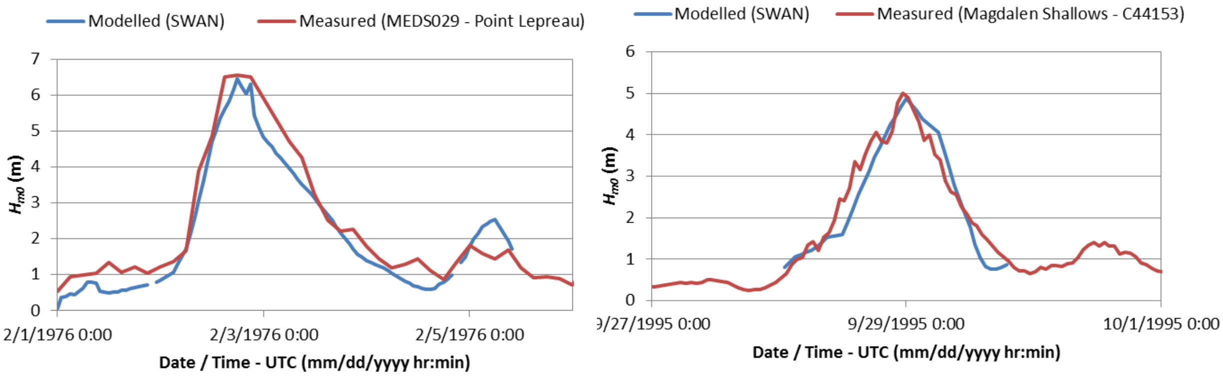

Figure 4: Measured and modelled significant wave heights at Point Lepreau (left) and Magdalen Shallows (right) during historical storm events.

2.3 Regional Wave Run-Up Calculations

Output from the regional wave transformation modelling 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 methodology for evaluating wave run-up involved two principal steps:

1. *Classification of the New Brunswick shoreline to define wave run-up sub-zones.* 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 was obtained from the CanCoast database (Manson et al. 2012). As the database did not explicitly identify seawalls (rock, concrete or other), which exhibit distinctive wave run-up characteristics, available satellite imagery was used to visually identify 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 used to classify the shoreline along Grand Manan Island, where CanCoast data coverage was not available. The resulting six shoreline classification types are listed in Table 1. Sub-classification of the shoreline into the six categories listed in Table 1 resulted in a total of 614 sub-zones; and

2. *Application of empirical formulae to calculate wave run-up.* For each sub-zone, wave run-up associated with the 1 and 100 year return period wind/wave conditions was estimated using an appropriate empirical formula, selected based on the shoreline classification type (Table 1). Calculated wave run-up heights for each sub-zone were expressed in terms of 2% run-up limits ($R_{u2\%}$).

Table 1: Shoreline classification types

Shoreline Classifiication Type	Backshore Slope (degrees)	Material Type	Wave Run-Up Formula
Cliff / bluff	> 45	> 45°	EurOtop II (2016), Eqn. 5.6
Mild-sloped beach	0 to 10	0° to 10°	U.S. Army Corps of Engineers (2002), Eqn. II-4-29
Steep-sloped beach	10 to 45	10° to 45°	EurOtop II (2016), Eqn. 6.21
Mudflat / marsh	0 to 10	0° to 10°	U.S. Army Corps of Engineers (2002), Eqn. II-4-29
Rock outcrop	0 to 45	0° to 45°	EurOtop II (2016), Eqns. 5.1 & 5.2
Seawall	N/A (visually identified)		EurOtop II (2016), Eqn. 1.4

3 RESULTS AND DISCUSSION

3.1 Offshore Wind and Waves

The offshore wind and wave data analysis revealed that storm sea states in New Brunswick offshore waters are typically bi-modal, comprising distinct wind sea (i.e. locally generated, high frequency) and swell sea (low frequency) components.

In the Southern Region, wind sea associated with storms typically propagates towards the open ocean (ENE to SE[1]), consistent with the dominant westerly winds (Figure 5). Swells generated by storms in the Atlantic Ocean propagate predominantly towards the WNW to N sectors into the Bay of Fundy. Based on the EV analysis for MSC50 grid point #M6003957 outside the Bay of Fundy (approximately 100 km south of Yarmouth, Nova Scotia, 102 m water depth), 1 in 1 year and 1 in 100 year return period significant wave heights reach up to 6.0 m and 10.6 m, respectively.

Extreme waves in the Gulf of Saint Lawrence are more typically associated with winds blowing over local fetches, and propagate towards the New Brunswick coast (through the E to NW sectors) as shown in Figure 6. Significant wave heights associated with the swell component of the wave spectrum infrequently exceed 5 m, and typically propagate from Cabot Strait towards the SW to NNW sectors. Based on the EV analysis for MSC50 grid point #M6013642 in the Gulf of Saint Lawrence (approximately 130 km east of the Acadian Peninsula, 80 m water depth), 1 in 1 year and 1 in 100 year return period significant wave heights reach up to 5.1 m and 8.4 m, respectively.

Further results and details of the offshore wind and wave analysis are presented in Cousineau et al. (2018).

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[1] Wave roses (Figures 5 and 6) are based on the directional convention used by the MSC50 database, i.e. the direction towards which waves propagate, expressed in degrees measured clockwise from true north. This is contrary to typical (i.e. nautical) convention adopted in coastal engineering literature, which expresses wave directions in terms of the direction from which waves propagate.

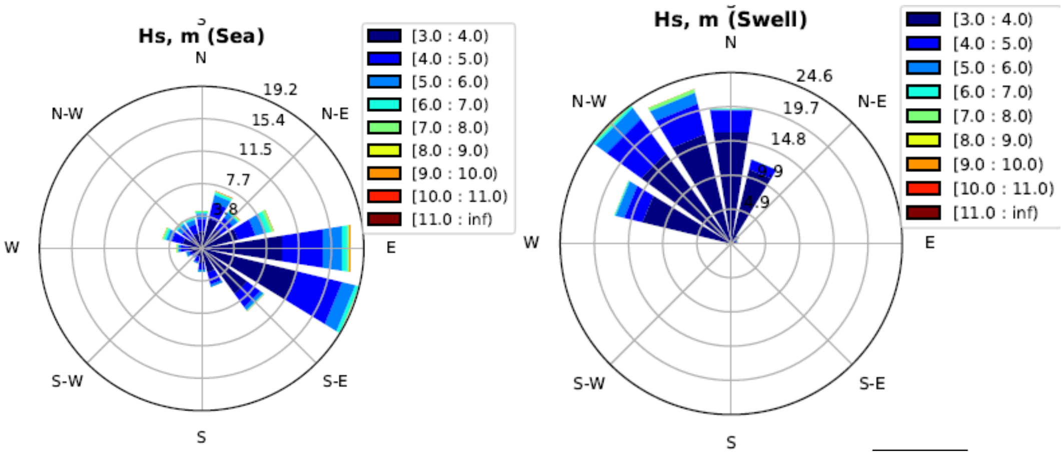

Figure 5: Significant wave heights exceeding 3 m associated with wind sea (left) and swell (right) components of wave spectra at an offshore location in the Southern Region (MSC50 grid ID #M6003957).

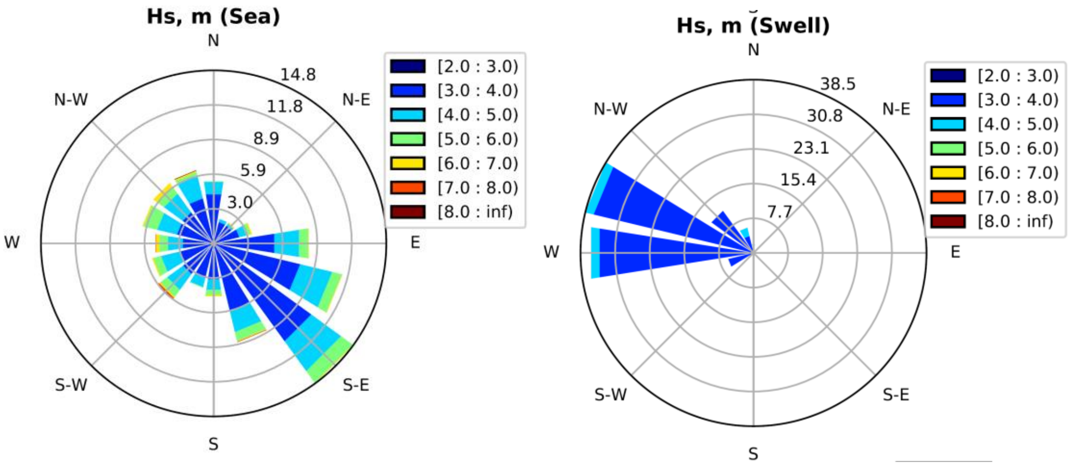

Figure 6: Significant wave heights exceeding 2 m associated with wind sea (left) and swell (right) components of wave spectra at an offshore location in the Northern Region (MSC50 grid ID # M6013642).

3.2 Nearshore Waves

Contours of 1 in 100 year return period significant wave height maxima (i.e. maximum values from all SWAN production simulations) are shown in Figure 7, and illustrate significant variability in exposure to extreme wave conditions across the New Brunswick coastal flood hazard zones.

3.3 Wave Run-Up

Calculated wave run-up heights for each sub-zone are shown in Figure 8 for the Northern Region and Figure 9 for the Southern Region. 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 1), wave run-up heights are proportional to the cross-shore slope, so computed $R_{u2\%}$ values tend to be 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. Under such circumstances, wave run-up may not be a useful indicator of the hazard level. Localized differences in shore conditions and/or the presence of structures may also result in actual wave run-up values that differ from the estimates. However, comparisons of site-specific wave run-up height estimates for two randomly selected locations to values for the encompassing sub-zones revealed relative errors in the range 11-26% (Cousineau et al. 2018), which is encouraging in terms of broad application of the study output.

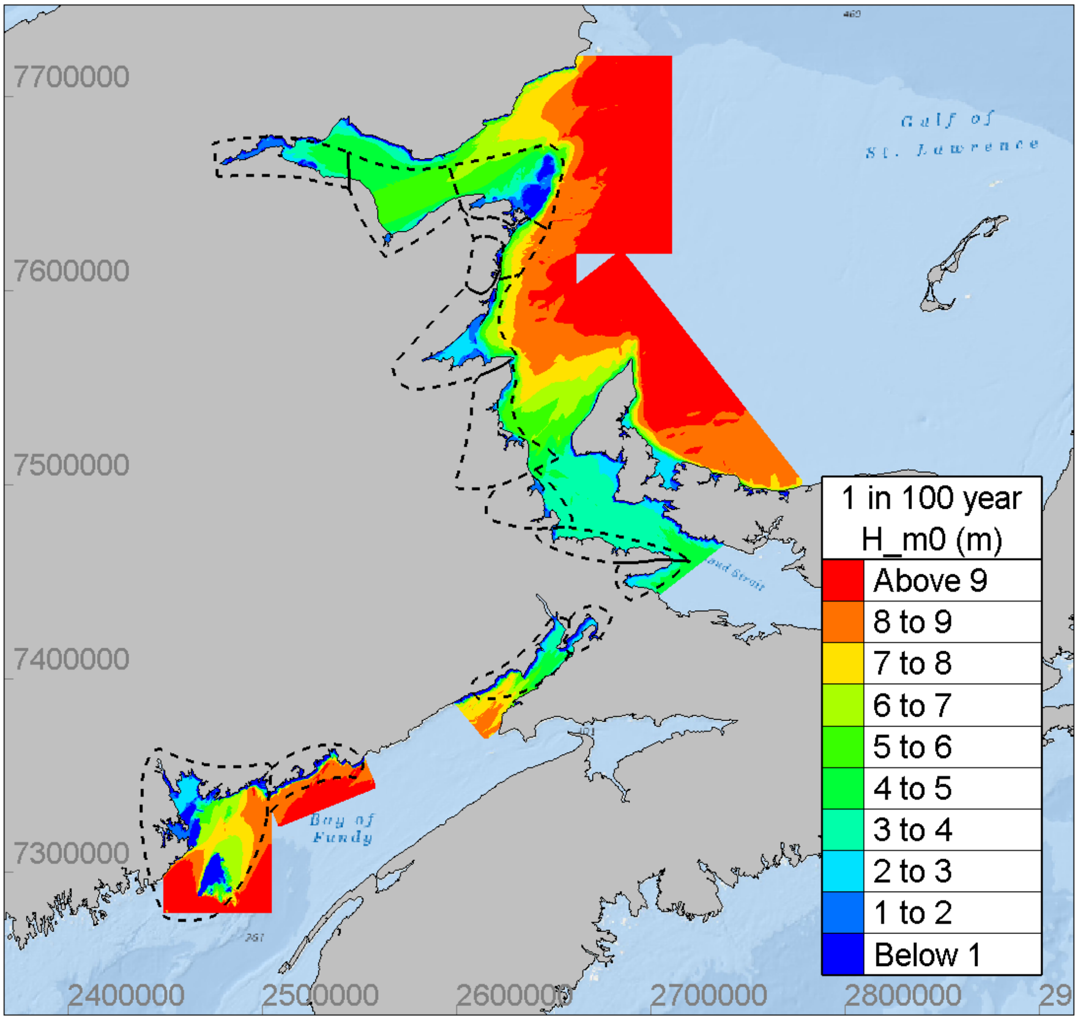

Figure 7: Modelled 1 in 100 year return period significant wave height maxima.

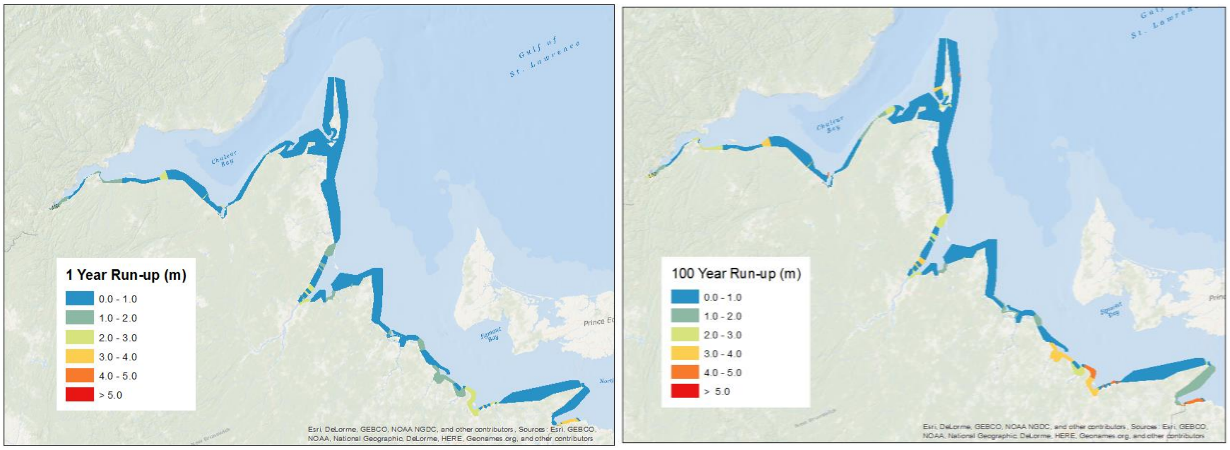

Figure 8: Calculated 1 year (left) and 100 year return period (right) wave run-up heights ($R_{u2\%}$) in the Northern Region.

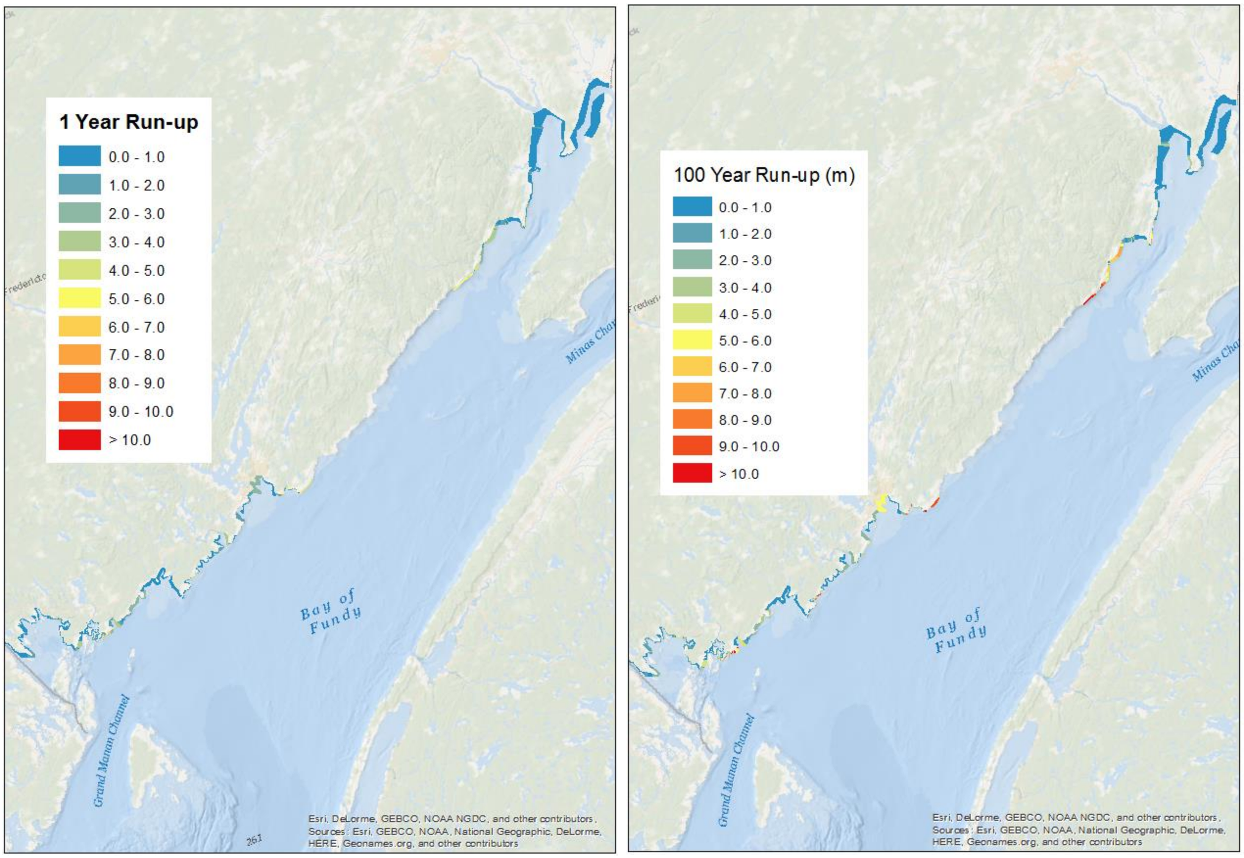

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Figure 9: Calculated 1 year (left) and 100 year return period (right) wave run-up heights ($R_{u2\%}$) in the Southern Region.

4 CONCLUSION

Extreme (storm) wave run-up heights were evaluated for 614 zones along the New Brunswick coast, applying a systematic, consistent methodology involving numerical modelling and geospatial data analysis. The wave run-up heights are based on representative nearshore extreme wave conditions and shore types (slope and physical features) for each zone. Accepting that localized differences in wave run-up heights or overtopping of coastal defences may occur, the geospatial output provides insight to the relative contribution of waves to overall coastal flood hazard potential in various regions of New Brunswick. The data will be disseminated through a publicly accessible, web-based map visualization tool, to improve awareness of coastal flood hazards and to support planning for community resilience.

The wave run-up estimates were based on extreme water levels including projections of relative sea level rise. Uncertainty surrounding future sea level rise rates has direct implications for the wave run-up height estimates. Exploratory research by the authors on the potential impacts of climate change on extreme winds and associated sea state conditions is not presented here. Further work on this topic is needed to facilitate an improved understanding of climate change impacts on coastal flood hazards in Canada.

The analysis was based on static topographic/bathymetric data. However, many parts of New Brunswick's coast are affected by erosion (Environment Canada 2006), storm-induced morphological change, and human intervention. These processes can alter incident wave conditions, wave run-up/overtopping performance and coastal flood hazards. Research is needed to predict future geomorphological change in Atlantic Canada and associated impacts on coastal hazards. Addressing these knowledge gaps will facilitate broader application of more sustainable, systems-based approaches to coastal zone planning and management, resulting in more resilient coastal communities.

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REFERENCES

Apostos, A., Raubenheimer, B., Elgar, S., and Guza, R. 2008. Testing and calibrating parametric wave transformation models on natural beaches, *Coastal Engineering*, **55**: 224-235.

Battjes, J., and Stive, M. 1985. Calibration and verification of a dissipation model for random breaking waves. *J. Geophys. Res.*, **90**(C5): 9159-9167.

Booij, N., Ris, R. C., and Holthuijsen, L. H. 1999. A third-generation wave model for coastal regions 1. Model description and validation, *J. Geophys. Res.*, **104**(C4): 7649-7666.

Brodtkorb, P.A., Johannesson, P., Lindgren, G., Rychlik, I., Rydén, J. and Sjö, E. 2000. WAFO - a Matlab toolbox for analysis of random waves and loads, *Proc. 10th Int. Offshore & Polar Eng. conf.*, **3**:343-350.

Cousineau, J., Pilechi, V., and Murphy, E. 2018. Regional Wave Run-Up Study for the Province of New Brunswick. NRC Technical Report OCRE-TR-2018-026, Ottawa.

Delft University of Technology. 2018a. SWAN User Manual.

Delft University of Technology. 2018b. SWAN Scientific and Technical Documentation.

Environment Canada. 2006. Impacts of Sea-Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick.

EurOtop II. 2016. Manual on Wave Overtopping of Sea Defences and Related Structures.

Goda, Y. 2010. Reanalysis of regular and random breaking wave statistics. *Coastal Eng.,* **52**(1): 71-106.

Government of New Brunswick. 2014. New Brunswick's Flood Risk Reduction Strategy.

Government of New Brunswick. 2016. New Brunswick Climate Change Action Plan.

Government of New Brunswick. 2018. LiDAR Download Map. https://geonb.snb.ca/li/

Holthuijsen, M., Herman, A., and Booij, N. 2003. Phase-decoupled refraction–diffraction for spectral wave models. *Coastal Engineering*, **49**: 291-305.

Hunter, J.D. 2007. Matplotlib: A 2D graphics environment. *Computing in Science & Engineering*, IEEE Computer Science, **9**(3): 90-95.

Manson, G. K., Coutoure, N., Forbes, D., Fraser, P., Frobel, D., James, T., Jenner, K., Lemmen, D., Lynds, T., Smith, C. and Szlavko, B. 2012. CanCoast: a national framework for characterising Canada's marine coasts, *Coastal Zone Canada Conference*, Rimouski.

Mazas, F., and Hamm, L. 2001. A multi-distribution approach to POT methods for determining extreme wave heights, *Coastal Engineering*, **58**.

Oliphant, T, E. 2006. *A Guide to NumPy.* Trelgol Publishing, USA.

R.J. Daigle Enviro. 2017. Sea-Level Rise and Flooding Estimates for New Brunswick Coastal Sections.

Ris, R. C., Holthuijsen, L. H., and Booij, N. 1999. A third-generation wave model for coastal regions 2. Verification, *J. Geophys. Res.*, **104**(C4): 7667-7681.

Swail, V. R., Cardone, V., Ferguson, M., Gummer, D., Harris, E., Orelup, E., and Cox, E. 2006. The MSC50 Wind and Wave Reanalysis, *9th International Workshop on Wave Hindcasting and Forecasting*.

U.S. Army Corps of Engineers. 2002. Coastal Engineering Manual, EM 1110-2-1100.

Zhai, L., Greenan, B. J. W., Hunter, J., James, T. S., Han, G., MacAulay, P., and Henton, J. A. 2015. Estimating Sea-Level Allowances for Atlantic Canada using the Fifth Assessment Report of the IPCC, *Atmosphere-Ocean*, **1**: 1-15.