CENTRE FOR MARINE APPLIED RESEARCH

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NOVA SCOTIA WIND-GENERATED WAVE EXPOSURE ATLAS

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Executive summary

A wind-generated wave exposure atlas has been developed as part of a larger effort by the Centre for Marine Applied Research (CMAR) to document near shore environmental conditions in Nova Scotia for the purpose of enabling safe aquaculture operations. Prevention of fish escapes is reliant on the engineering of containment systems which consider the local wind and wave climate. Loading on containment systems is dominated by wind, wave and current conditions at the sites. Therefore, understanding how 'exposed' an existing or potential site is to wave and wind, provides significant value to the aquaculture industry and stakeholders.

The purpose of the wind-generated wave exposure atlas described herein is to provide a tool that allows one to quickly compare the relative exposure to wind-induced waves between different areas in coastal Nova Scotia. This will allow both the province and the aquaculture industry to quickly assess the relative severity in wave conditions at existing and potential future sites for finfish, shellfish and seaweed aquaculture.

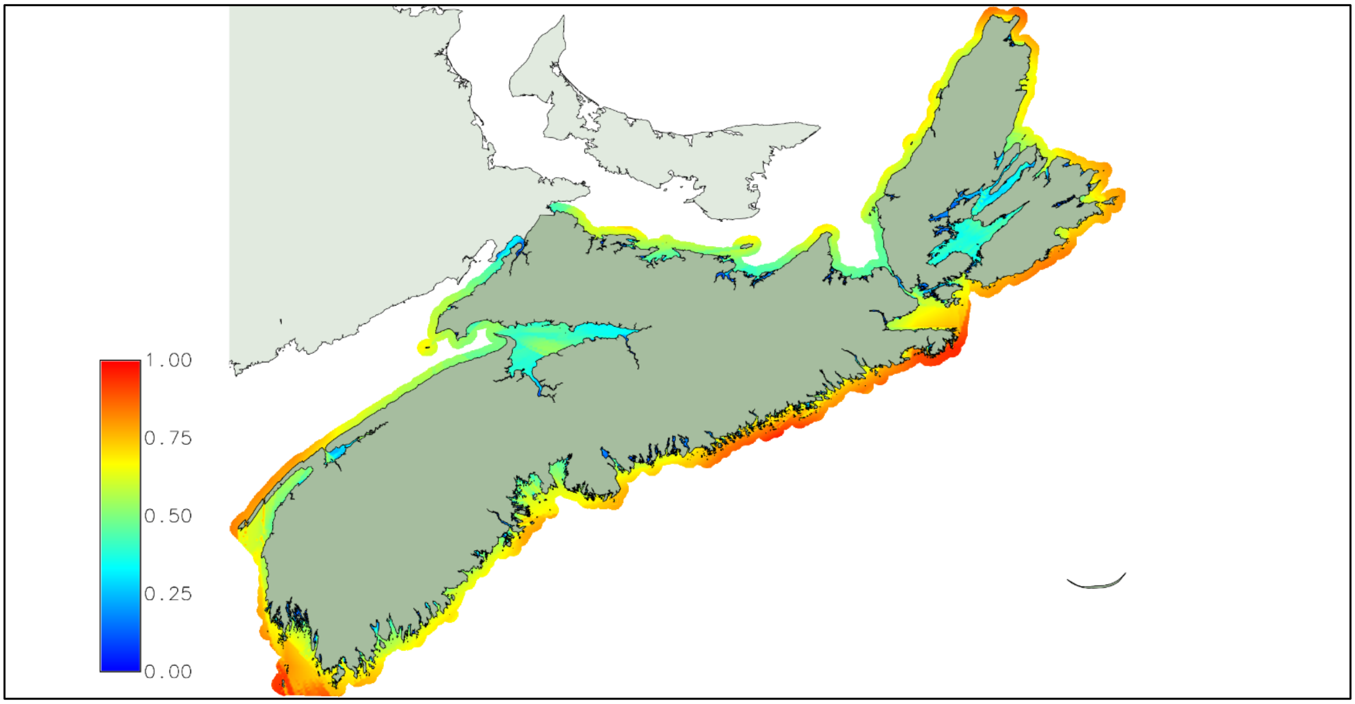
The scope of the project has been limited to coastal regions within 5km of the of Nova Scotia shoreline. The atlas is also limited to wind driven waves only. The influence of swell is not considered. However, locations which are exposed to ocean swell are clearly identifiable in the atlas due to their large fetch in exposed sectors.

The approach used for the atlas follows the methodology used in the Norwegian aquaculture industry [1]. A historic wind record has been obtained from the ECMWF ERA5 dataset for the past 10 years [2]. For each hour in the time series, the wind speed is combined with the fetch computed in the direction in which the wind is coming from. Empirical wave growth forecasting formulas are used to compute a significant wave height. The maximum significant wave height over the 10-year duration is used as the basis for the wave exposure.

This process has been repeated at approximately 35,000 points distributed around the province. The points have been distributed with approximately half the points within 1km from the shoreline, and the remaining points are located between 1km and 5km from the shoreline. The results from these points have been interpolated to produce a map of the wave exposure as shown below.

The results of the wave exposure have been provided to CMAR at a resolution of 250m for use on Nova Scotia's Fisheries and Aquaculture site mapping tool [3].

To demonstrate how the wave atlas can be used this report contains a sample assessment of Jordan Bay and Shelburne Harbour using the wave atlas and cross referencing it with results from the wind and wave reports from the same locations. The results of the comparison show that there are similarities between the wave atlas exposure index and significant wave heights. Sites with an index below 0.4 show lower significant wave heights lower wave heights while the more exposed sites with and index above 0.4 show higher significant wave heights.



Nova Scotia Wind-generated Wave Exposure Map

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1 Introduction

1.1 Purpose

A wind-generated wave exposure atlas has been developed as part of a larger effort by the Centre for Marine Applied Research (CMAR) to document near shore environmental conditions in Nova Scotia for the purpose of regulating aquaculture operations. The purpose of the atlas is to provide a comparison of the exposure to wind induced wave between different areas of the Nova Scotia. This will allow both the province and the aquaculture industry to quickly assess the relative severity in wave conditions between existing and potential future sites.

1.2 Scope

The scope of the project is limited to coastal regions of Nova Scotia. For the purpose of this report, coastal waters have been defined as the marine region within 5km of the shoreline. The project is also limited to wind driven waves only. The influence of swell is not considered.

1.3 Background

Wave exposure atlases have been used by both Scotland and Norway to gauge the relative exposure to aquaculture sites [4] [1]. DSA has developed the Nova Scotia wind-generated wave exposure atlas based on the approaches used by Scotland and Norway.

The approach used by Scotland has been to consider only the influence of fetch, and develop an exposure index that considers the extent to which a location is exposed to large fetches. This approach does not account for variations in wind speeds that are anticipated across Nova Scotia, particularly the presence of tropical storms and hurricanes on the eastern coast of Nova Scotia. The approach also does not consider local variations in the prevalent storm wind directions. Although a location may be exposed to fetch, it may not be aligned with the prevalent wind direction that occurs during a storm. The government of Scotland has computed the exposure index for the entire country and made the data available for public use [5].

The methodology used in Norway considers the combination of fetch and wind speed. Wind speeds are combined with the fetch in the corresponding directions, and used to compute wave heights using empirical forecasting methods. This method overcomes the limitations of the Scottish wave exposure index. However, to the authors knowledge, the analysis has only been computed for a limited number of aquaculture sites and has not been made available for future sites.

2 Abbreviations and acronyms

DSA	Dynamic Systems Analysis Ltd.
CMAR	Centre for Marine Applied Research
ECMWF	European Centre for Medium-Range Weather Forecasting
F	Fetch
H_s	Significant wave height
U_a	Wind stress
U_{10}	Wind speed component at 10m above sea level in east-west direction
V_{10}	Wind speed component at 10m above sea level in north-south direction
$\vec{U}_{10}$	Wind speed vector at 10m above sea level

3 References

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[8] International Organization for Standardization, "ISO 16488: Marine finfish farms - ope net cage - design and operation," 2015.

[9] M. Karimi, "Wind and Wave Conditions – Jordan Bay – Marine Finfish Leases 1358, 1359," DSA, Victoria, BC, 2020.

[10] M. Karimi, "Wind and Wave Conditions – Shelburne - Marine Finsfish Leases 1345, 0602, 1192, 0983 ," DSA, Victoria, BC, 2020.

4 Overview

The high variability of coastal regions around Nova Scotia lead to different types and levels of wave action. Waves are broadly classified into two different types: wind-generated waves and swell. Wind-generated waves, or wind waves, are waves that are produced by locally occurring weather systems. Wind in the immediate vicinity act upon the water surface and lead to the development of waves. Swell on the other hand is generated by remote storm systems. Wave are generated in the location of the storm, which are then propagated to the coastal regions. Due to changes in the waves as they propagate over long distances, the characteristics of well differ from that of wind-generated waves. Wind-generated waves tend to be steeper with a shorter period.

The height and period of wind driven waves is influenced by three factors:

1. The wind speed
2. The duration in which the wind blows
3. The distance over which the wind blows (known as fetch)

The other factor that will influence the development of waves is the bathymetry. The presence of the coastal features such as bays and headlands will lead to wave diffraction, which is the process whereby waves travelling at an angle to the shoreline will bend towards the shore. This leads to a dispersion of wave energy in bays, and a concentration of wave energy near headlands. Shallow water also causes large waves to break limiting the maximum wave height. Other than the calculation of fetch, the influence of the coastal features and bathymetry is not account for in the wave exposure. This may result in exaggerated wave exposures in shallow water. However, as finfish aquaculture sites are typically located in areas with similar water depths, it is not expected to influence the relative exposure between existing or potential aquaculture sites.

5 Methodology

5.1 Overview

An application has been developed by DSA to model the exposure of a location to wind induced waves. The calculation of wave exposure generally follows the approach used in Norway [1]. The general procedure for calculation of the wave exposure is shown in Figure 1. The process begins by identifying a potential location of interest. The discrete point of interest is defined by its geographic coordinates. A historical record of wind conditions, including speed and direction, are then determined at the chosen location. The fetch is computed for each wind direction by determine the distance to the nearest shoreline in the direction in which the winds are coming from. The fetch and wind speed records are then used to calculate a time record of wave height. Statistics are then extracted from the time record of wave heights and used to develop an exposure index. Each of these steps is further discussed in the sections below.

Figure 1. General process of calculation of wave exposure

To produce an exposure map similar to that provided by Scotland [5], the above process has been repeated for a large number of discrete points around Nova Scotia. The result is a wave height value for each point covering the entire coastal region of Nova Scotia. A map of wave exposure values has been produced by interpolating the wave exposure at the selected points for all locations around coast of Nova Scotia.

5.2 Use of wave exposure index

The wave height values calculated have been non-dimensionalized by normalizing with the maximum value from all points used to develop the atlas. This wave index value is provided because in more exposed areas, the wave heights produced are not the true maximum wave heights that could be expected at a location due to meteorological or bathymetric influences. The wave index cannot be used to directly engineer systems as the 1 in 10 and 1 in 50 year return period extreme wave height and corresponding peak periods are not reported.

The index value provides one with a tool to assess the relative exposure within the province. For example, given the wave conditions and wave index at a known active aquaculture site, one can use the wave exposure index to surmise potential minimum increase in wave heights that could be expected moving to another location with a known wave index value nearby. Through this method, known exposure index levels which are potentially suitable for aquaculture can be determined.

5.3 Location Selection

Discrete points have been selected for the calculation of wave exposure. To ensure accuracy of the resulting wave exposure map, it was necessary to have a high density of points where the exposure has the potential to change significantly over short distances. As the spatial variation in wind speed is low, the predominate factor influencing the required point spacing is local changes in fetch. Therefore, a dense spacing of has been used near the shore and a reduced spacing in open areas.

To achieve the above result, two regions have been generated. First, the shoreline has been defined based on the Province of Nova Scotia's county boundaries [6]. Two regions were then generated: one extends from the shoreline to 1km from the shore while the second region ranges from 1km to 5km from the shoreline. This boundary has been extended in key areas around the province including St. Mary's Bay and Chedabucto Bay to ensure that the entire bay has been included in the atlas. Points were then generated within these regions with a spacing of 500m and 1000m respectively. An example of the points produced using this methodology are shown in Figure 2.

The methodology has resulted in a total of 35,014 points distributed around the province. Approximately half of these are located with 1km of the shoreline, while the other half is between 1km and 5km from shore.

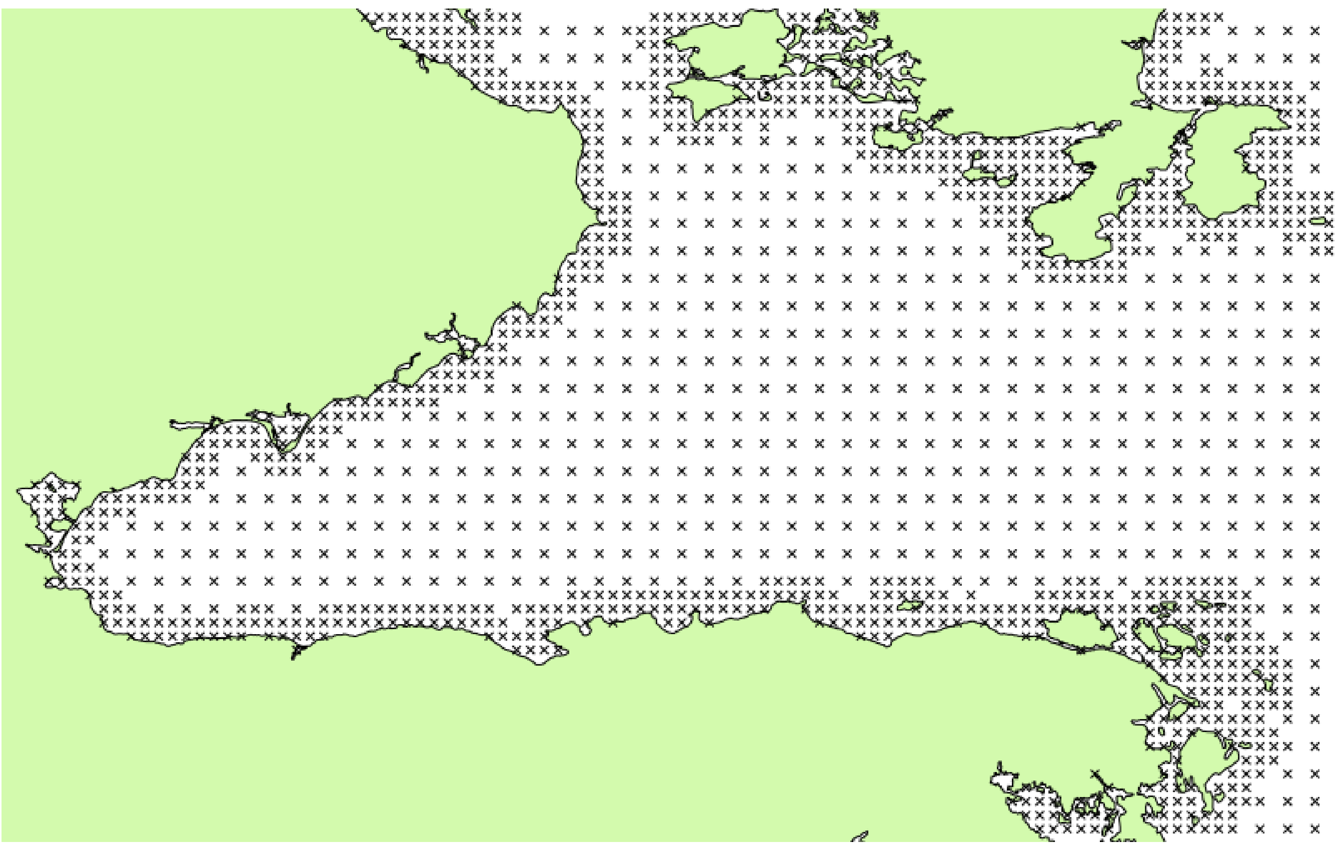

Figure 2. Example site spacing for calculation of wave exposure in Chedabucto Bay

5.4 Wind Data

Historical wind data has been obtained from the ECMWF ERA5 dataset [2]. The ERA5 dataset is a worldwide reanalysis, which uses numerical weather forecasting models combined with historical weather observations to produce a complete time series of worldwide weather. The ERA dataset has been obtained for the area covering Nova Scotia for the time period from January 1, 2010 to December 31, 2019. The wind speed components (U10 and V10) at 10m above the sea surface have been used to determine the wind speed and direction.

The ERA5 dataset has a temporal resolution of 1 hour, and a spatial resolution of 0.25 degrees. To determine the wind speed and direction at each individual point, the individual wind components have been linearly interpolated. This approach provides a smooth transition of wind speeds between points.

5.5 Fetch Calculation

Fetch is defined as the distance between the point of interest and the shoreline in the direction in which the wind is coming from. To ensure a gradual transition in exposures between adjacent points, an exact method of computing fetch for each wind direction has been utilized. This approach differs from that used in Scotland and Norway in that discrete directional bins have not been used. The calculation of fetch is divided into two steps. First, a fetch polygon is generated to speed up future fetch calculations. Secondly, the fetch polygon is used to compute fetch in any specific direction.

The fetch polygon is defined as the polygon containing all locations that have a direct line-of-sight with the point of interest. It is the polygon that would be produced by extending an infinite number of rays outward from the point until they intersect with a land boundary. An example fetch polygon is shown in Figure 3.

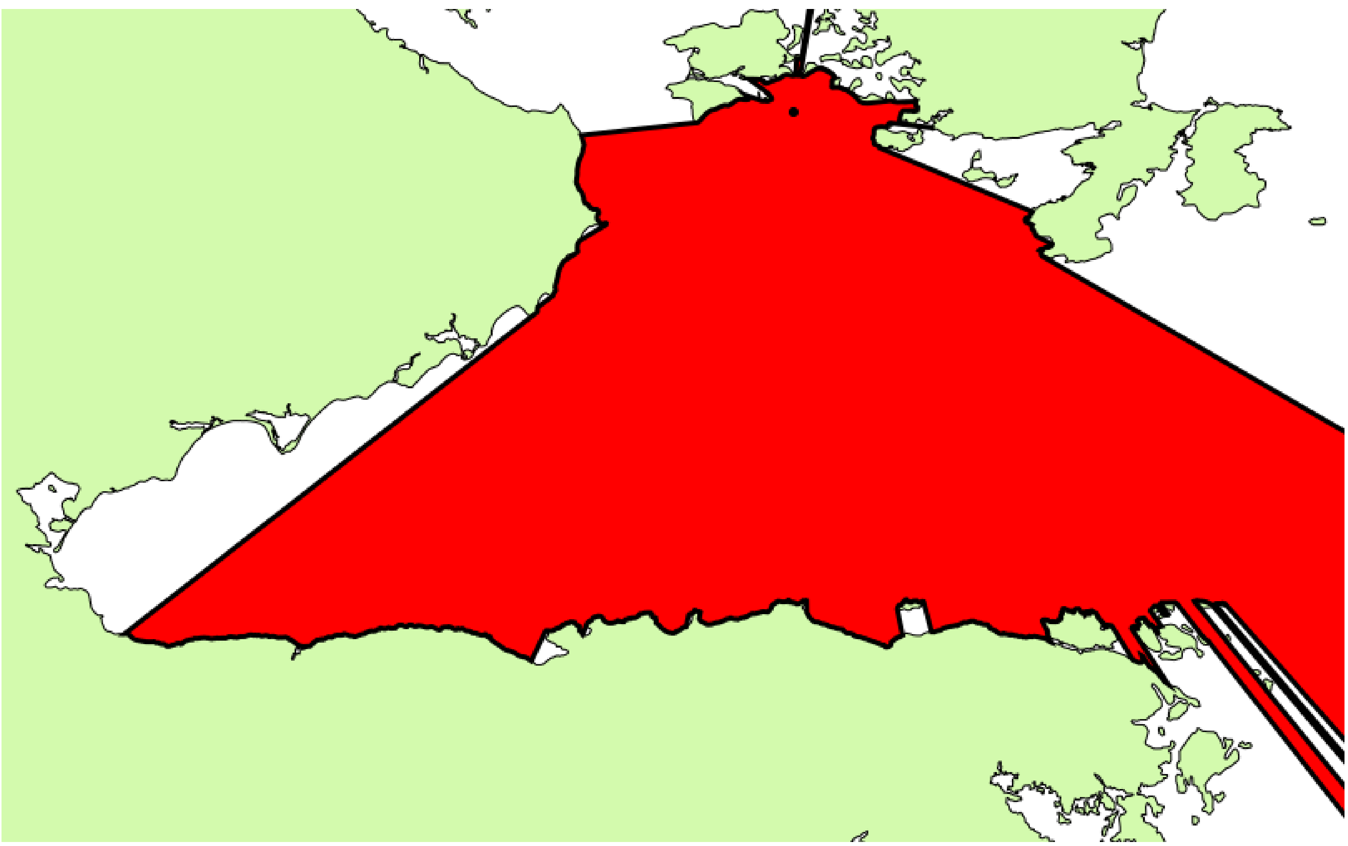

Figure 3. An example fetch polygon from Chedabucto Bay
Fetch polygon is the red area. The point of interest is shown as a black dot near the northern part of the fetch polygon.

To generate the fetch polygon, the Province of Nova Scotia's county boundaries [6] were merged with the Canadian Government's census boundary for PEI and New Brunswick [7]. Use of a Canadian wide coastline file was important to generate accurate fetch estimates where the fetch is limited by the coastline of other provinces. This is the case for example in the Bay of Fundy, where the fetch is limited by the coastline of New Brunswick on the opposite side of the bay. Prior to computing the fetch, the boundary file has been converted to UTM Zone 20 coordinates.

Once the fetch polygon for the point is computed, calculation of the fetch is straight forward. A ray is extended in the direction that the wind is coming from, and the polygon edge in which the ray intersects is identified. The distance from the point of interest to the intersection point is the fetch.

5.6 Wave Calculation

Wave heights have been calculated using empirical formulae for fetch limited wave growth from the ISO 16488 standard for marine finfish farms [8]. The calculation of significant wave height is given by the equations below. These equations have been plotted in Figure 4. A maximum fetch of 40km has been imposed. This maximum is used whenever the fetch is unbounded due to exposure to the open ocean. This cap on the fetch will restrict the maximum wave height that can be generated for a specified wind speed.

$$H_s = 5.112 \times 10^{-4} U_a \sqrt{F}$$

$$U_a = 0.71 \left| \vec{U}_{10} \right|^{1.23}$$

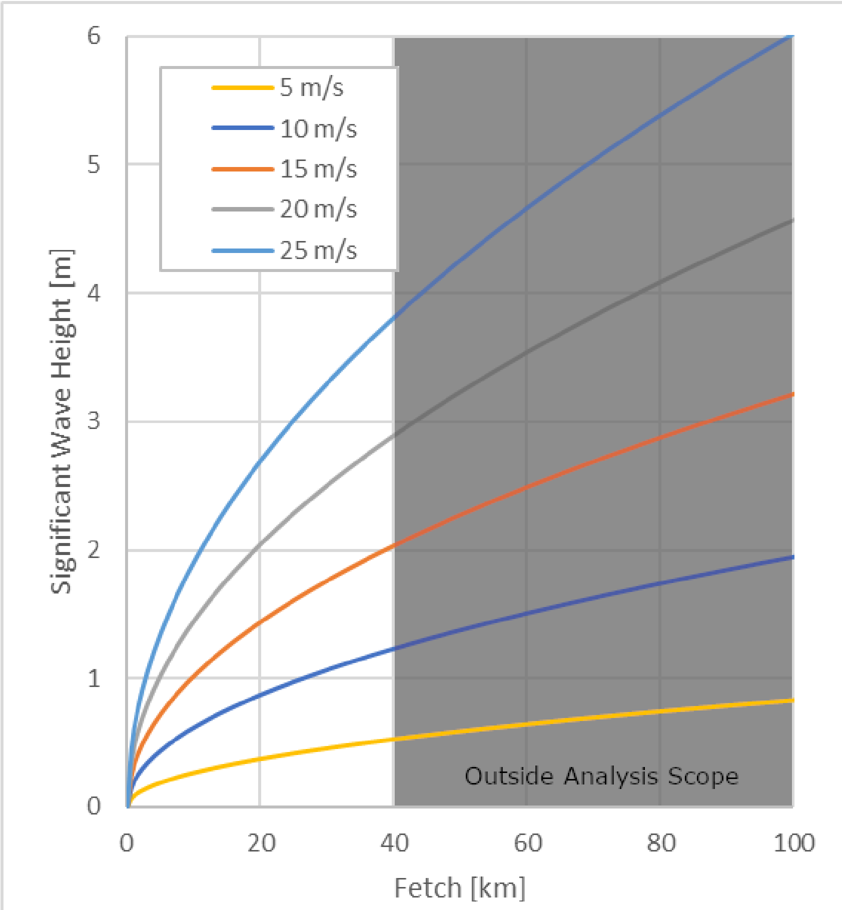

Figure 4. Empirical wave forecasting equations
Grey region shows where wave height calculations have been capped due to restricting the fetch to a maximum of 40 km

The wind speeds used in the above equation are taken directly from the ERA5 dataset on an hourly basis. The above equations are appliable for fetch limited waves, which implies that the wind has been acting on the surface long enough to generate a steady wave condition. For long fetches, the duration required to obtain a fetch limited wave may be significantly longer than the 1-hour resolution of the ERA5 dataset. Therefore, the use of 1-hour values is a conservative estimate of the wave heights. However, as the goal of the wave atlas is to provide a comparative estimate of exposure across different locations, a long as this conservatism is applied equally across all locations, the non-dimensional exposure index should not be affected.

6 Results

The results of the wave exposure atlas are provided in Figure 5 for the complete province. This data has been provided to CMAR at a resolution of 250m. As an example, a closeup of the wave exposure atlas for Chedabucto Bay is shown in Figure 6.

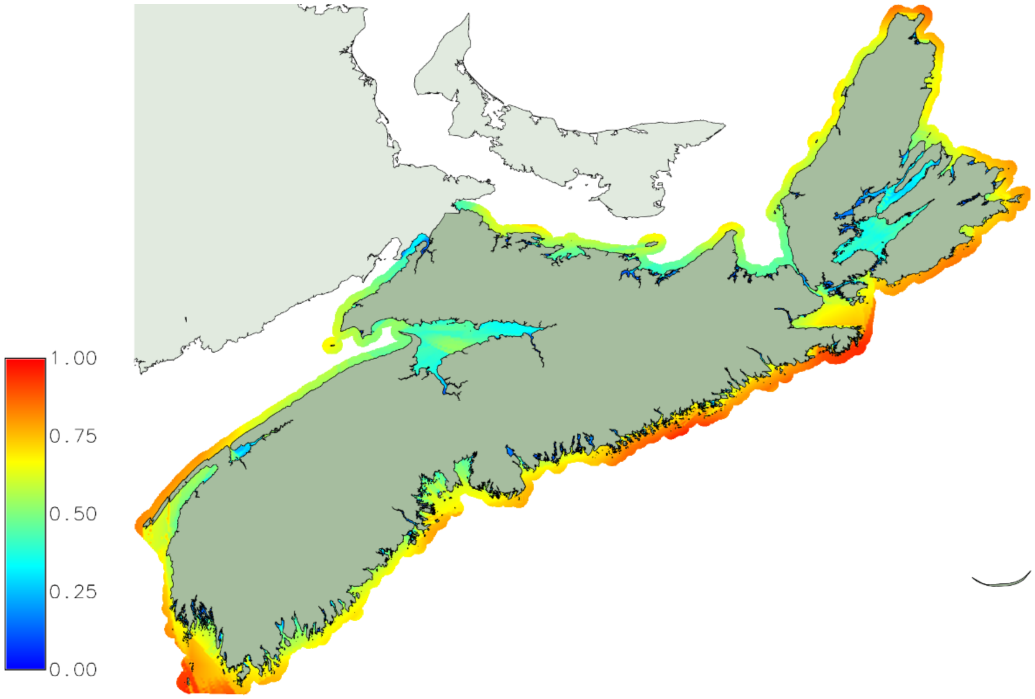

Figure 5. Wave exposure index for entire province of Nova Scotia

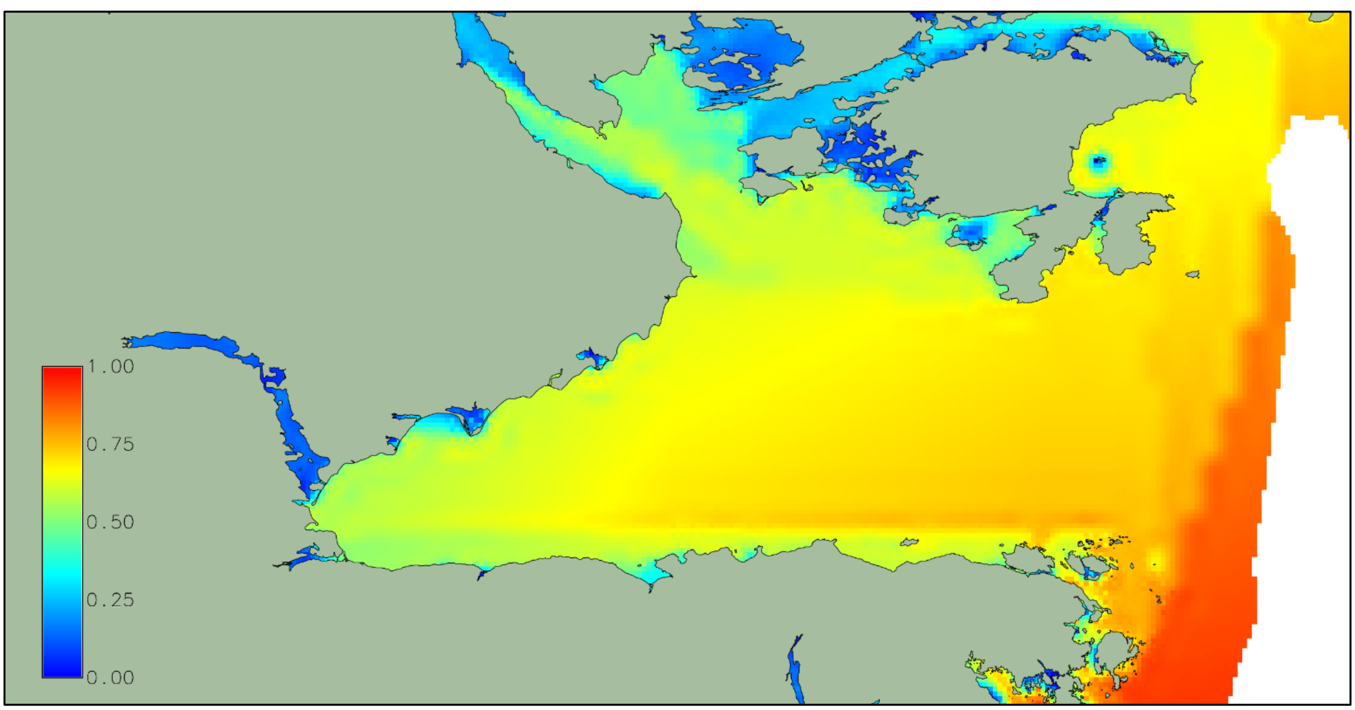

Figure 6. Close up of wave exposure index for Chedabucto Bay

6.1 GIS Wave Atlas Layer

The results of the wave exposure atlas are provided in figure 5 for the complete province. This data has been provided to CMAR at resolution of 250m in the GeoTiff format. As an example, a closeup of the exposure atlas for Chedabucto Bay is shown in figure 6.

6.2 Sample assessment of Jordan Bay and Shelburne Harbour sites using wave index

To demonstrate how the wave index can be used, Figure 7 shows the exposure index for aquaculture sites in Jordan Bay and Shelburne Harbour. The index can be used to judge site exposure to wind driven waves. As illustrated below the more protected sites 0983, 1192, 0602 show a much lower exposure index to sites 1359 and 1358 which are situated in more exposed locations.

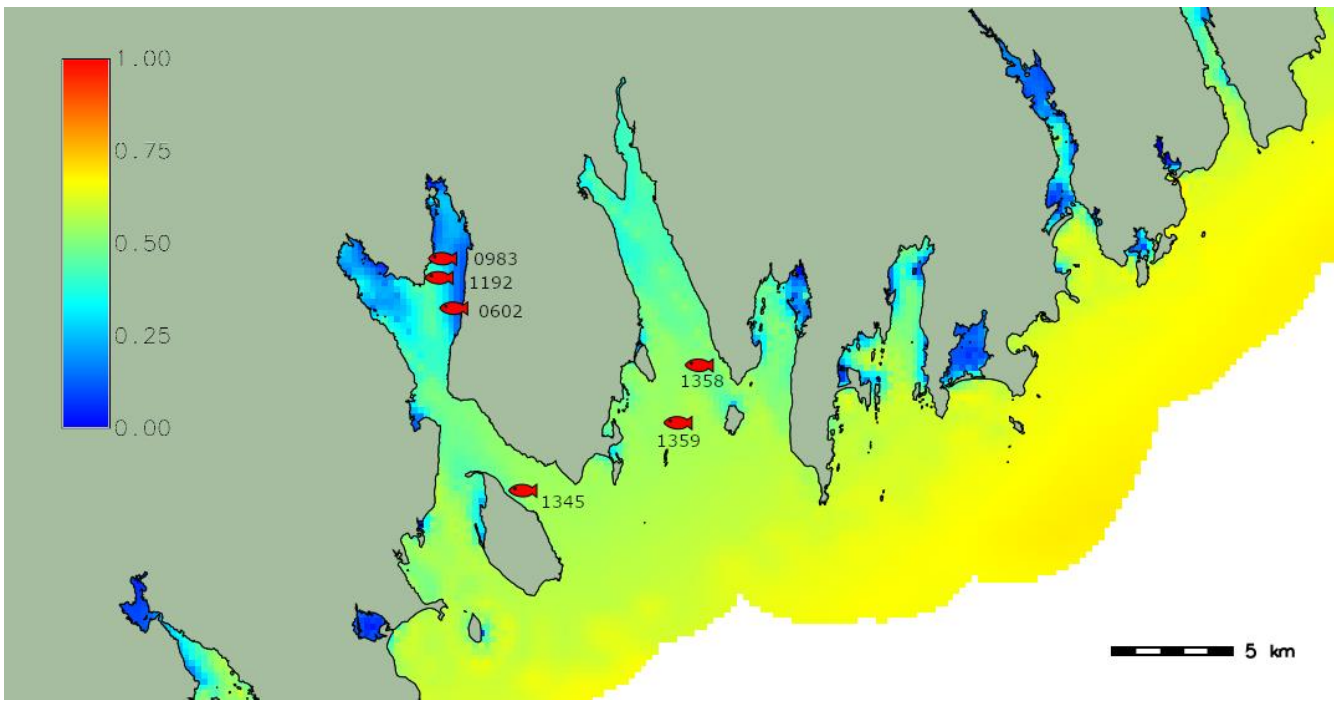

Figure 7 Wave index map of Shelburne Harbour and Jordan Bay finfish sites. The wave index colour scale is shown in the upper left of the figure.

Lease Id	Wave Atlas Exposure Index	10 Year maximum significant wave height	50 Year maximum significant wave height
0602	0.20	0.77	0.82
0983	0.27	0.94	1.12
1192	0.37	0.9	1.08
1345	0.53	2.62	2.03
1358	0.49	2.74	3.42
1359	0.54	3.66	4.56

Table 1 Comparison of the exposure index to 10 and 50 year maximum significant wave heights (m). Significant wave height data was extracted from the Wind and Wave Reports for Jordan Bay [9] and Shelburne Harbour [10].

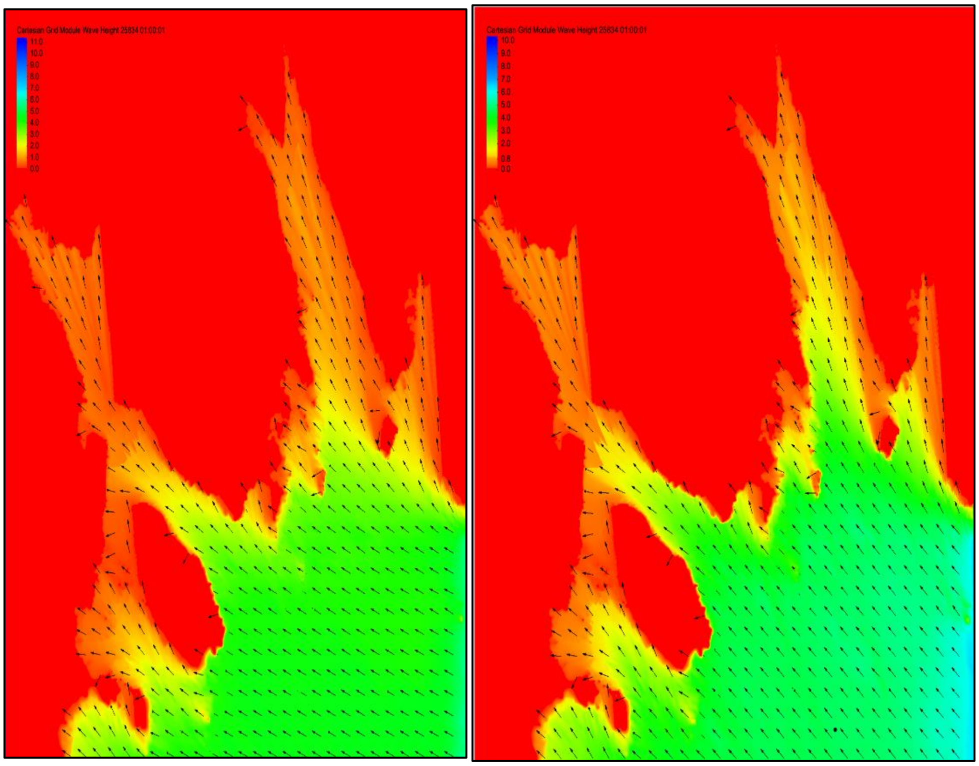

Figure 8 Wave modeling results for Shelburne Harbour direction (from) 133 deg ESE and 135 deg SE

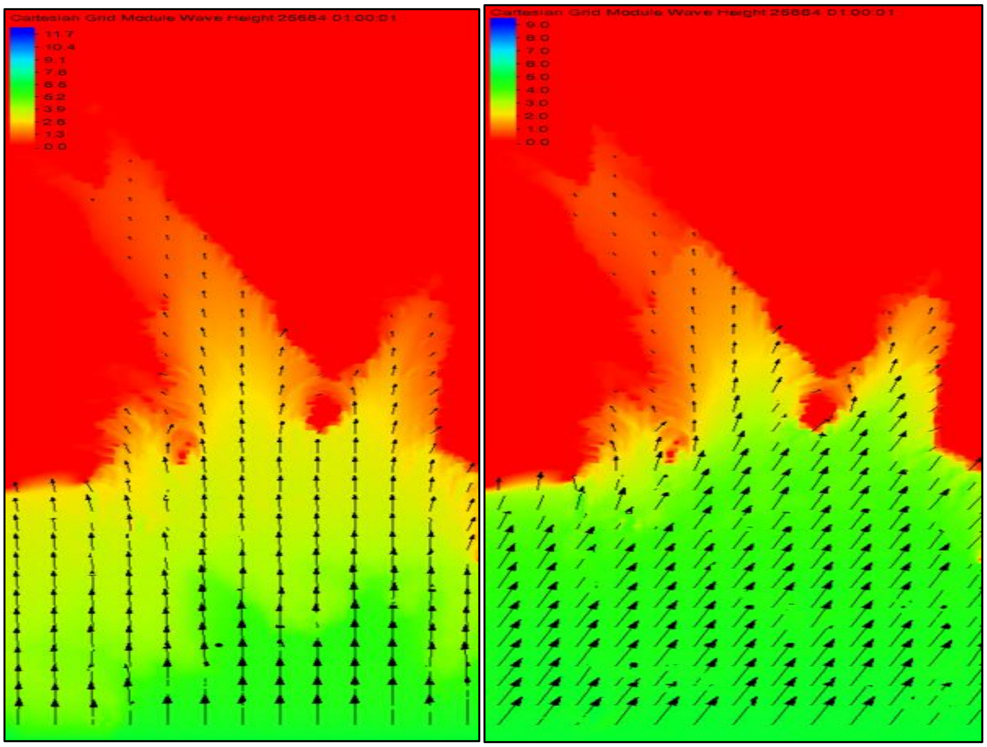

Figure 9 Wave modeling results for Jordan Bay (from) 180 deg S and 203 deg SW

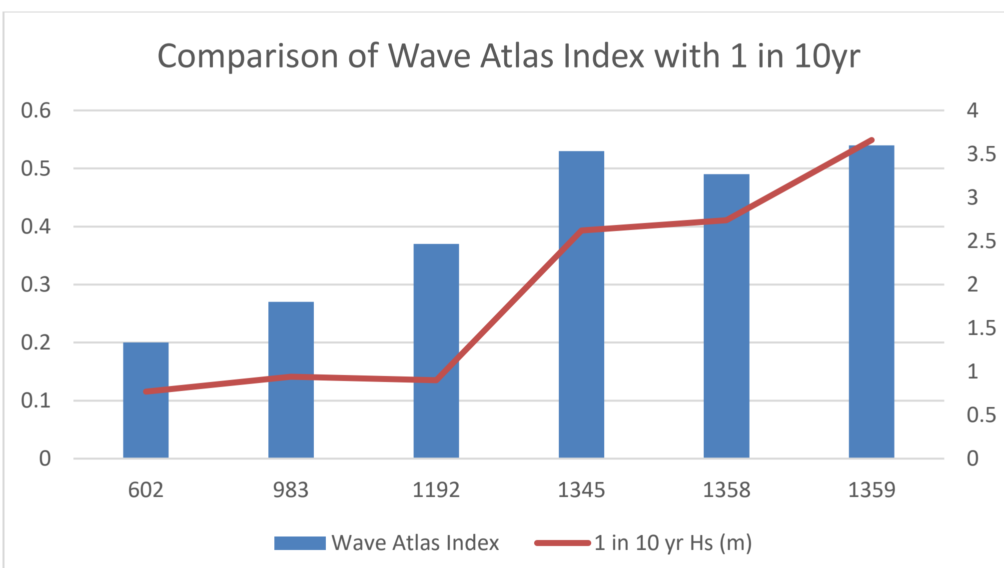

Figure 10 Comparison of the Wave Atlas Index and 1 in 10 year Hs (m)

The comparison of the wave index and 10 year and 50-year wave heights show that the two data sets follow a similar trend. The lowest wave index point is 0.20 for lease 0602 in Shelburne Harbour and the corresponding wave heights of 0.77 for the 10-year maximum height and 0.82 for the 50-year maximum height are the lowest recorded of the sample locations. When looking at the highest index recording of 0.54 for site 1359 in Jordan Bay the corresponding wave heights are also the highest for the sample area. The remaining four points follow the same trend.

Based on the sample assessment the sites 0602, 0983 and 1192 in Shelburne Harbour have a wave atlas index less than 0.4 and show lower significant wave heights. While the sites 1358 and 1359 in the more exposed Jordan Bay and site 1345 by McNutts Island show an exposure index of greater than 0.4 and also show higher 1 in 10-year significant wave heights. This trend is visible in figure 8. Although this trend is not a proportional lineal increase between the exposure index and significant wave height it is a valuable indicator as to what wave conditions may be present at current and future site locations.