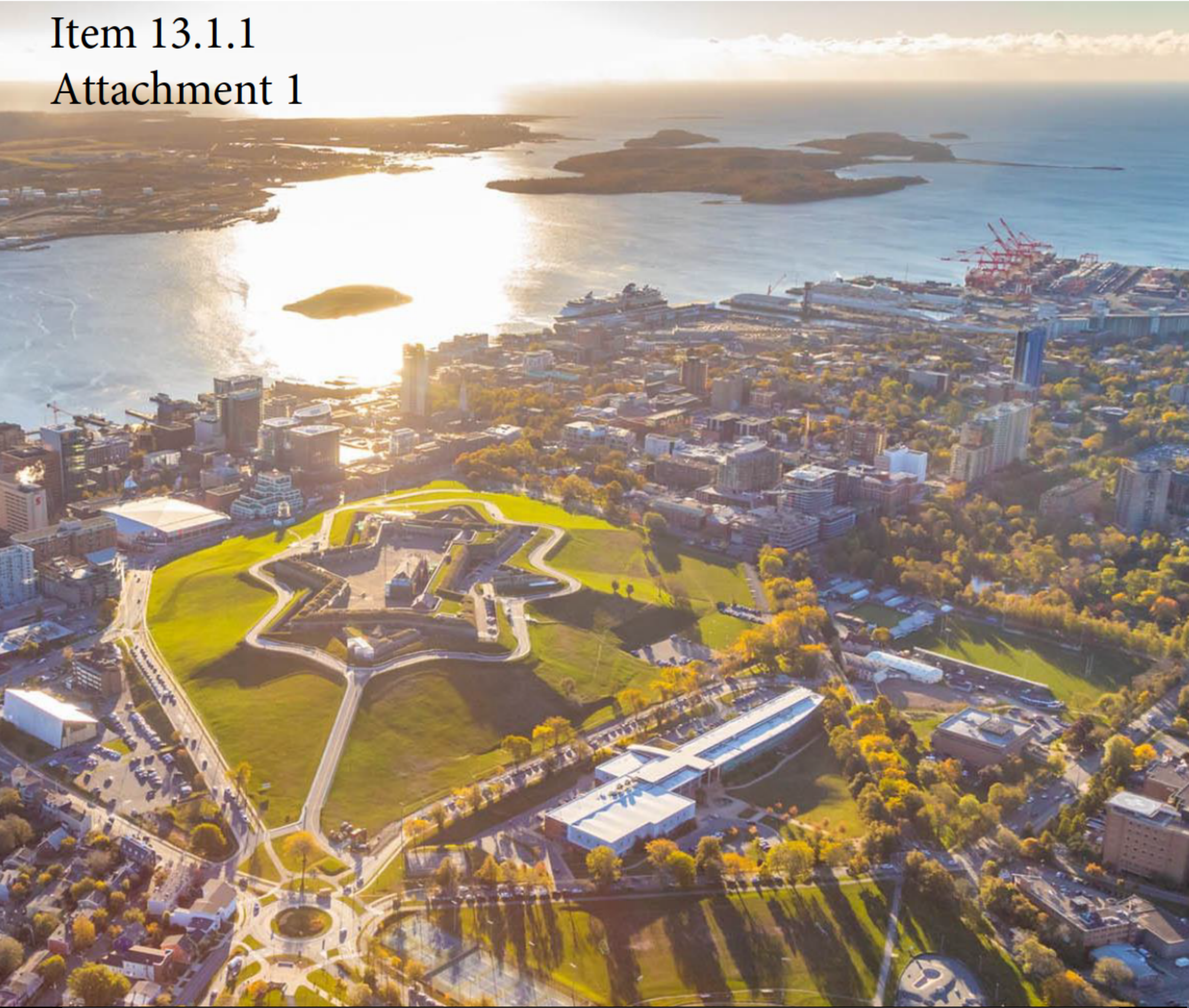
Item 13.1.1
Attachment 1



HRM Extreme Water Levels
2022

Prepared by:

CBCL

Prepared for:

HALIFAX

221150.00 • July 2022

	Updated Final	V. Leys	July 20, 2022	A. Camarena G. Mauti
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Issue or Revision		**Reviewed By:**	**Date**	**Issued By:**

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July 20, 2022

Samantha Page, M.Sc.
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Dear Ms. Page:

RE: Final – Halifax Regional Municipality Extreme Water Levels

The CBCL Coastal Team is pleased to submit this FINAL report of the Halifax Regional Municipality Extreme Water Levels. Please do not hesitate to contact the undersigned with any questions or comments you may have with regards to the contents of this report.

We look forward to your feedback prior to finalizing the report

Yours very truly,

CBCL Limited

[redacted]

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Project No: 221150.00

Executive Summary

A desktop review of extreme static water levels in Halifax Regional Municipality (HRM) was completed to produce a summarized document of extreme water levels, which can be used by decision makers, planners, and consultants to determine potential coastal flooding hazards. Extreme static water levels include the effects of tides, storm surge, and sea level rise.

Five coastal zones were defined in HRM, which were based on areas with similar coastal conditions and shorelines. Extreme water levels are provided for each of the coastal zones. A map of the coastal zones is illustrated in Figure i.

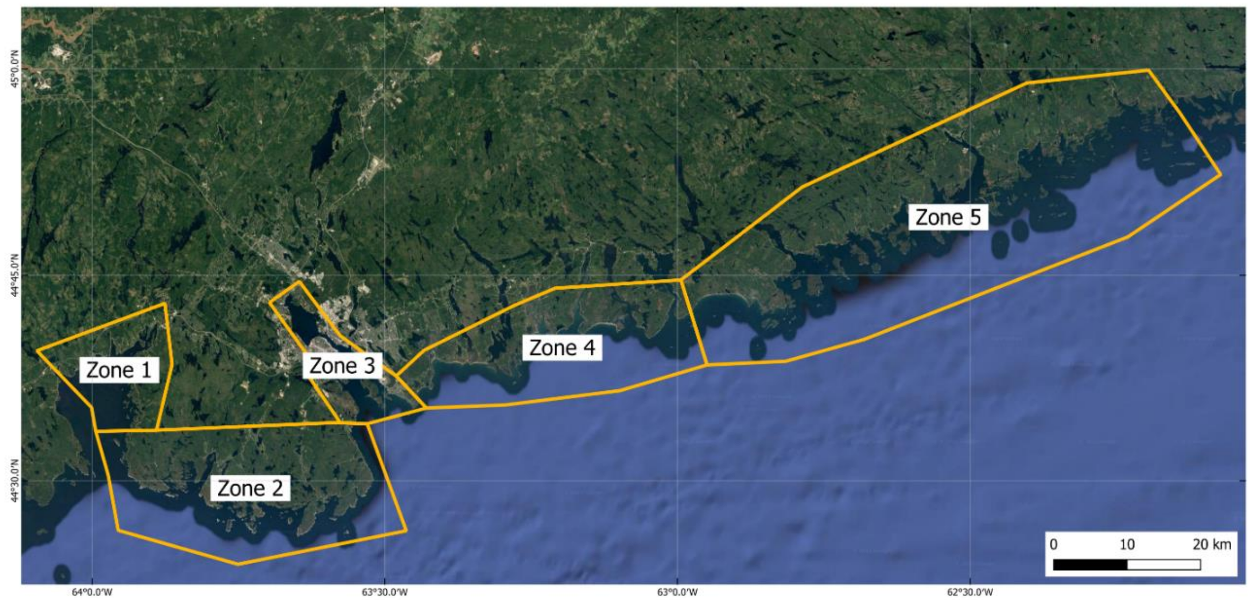

Figure i: Map of five coastal zones established for HRM extreme water levels study.

Tidal elevations were derived from Department of Fisheries and Oceans (DFO) data sources, including Canadian Hydrographic Services tide tables (CHS) and the Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT). Both sources provide tidal elevations across Canada. Three different tidal elevations were provided for each coastal zone including HHWLT, MWL, and LLWLT[1]. A conservative approach was used to determine the appropriate tidal elevation for each zone by using the maximum HHWLT in each coastal zone from both sources and the corresponding tidal elevations to that location.

Extreme water levels due to storm surge were calculated using a statistical analysis (extreme value analysis) where long-term tide gauge data was available (Zone 3). For zones without long-term tide gauge data, an existing storm surge hindcast was used to calculate

[1] Higher High Water Large Tide (HHWLT), Mean Water Level (MWL), Lower Low Water Large Tide (LLWLT)

the extreme water levels (Zone 1, 2, 4, and 5). For this method, the storm surge residual was added to the HHWLT to calculate the extreme water level. The return periods (RP) for the extreme water levels provided in this analysis include 2-, 5-, 10-, 20-, 50- and 100-year RP storms for all coastal zones and additionally, 200-, 500-, and 1000-year RP storms for Zone 3.

Sea level rise projections were derived from the Fifth Assessment Report (AR5, IPCC 2013) and the Sixth Assessment Report (AR6, IPCC 2021) published by the Intergovernmental Panel on Climate Change (IPCC). For projections from the AR5, regionally specific projections calculated by Natural Resources Canada were used for the various coastal zones (James *et al.*, 2021). The projections included in this study from the AR5 was RCP4.5 median values, RCP8.5 median values, RCP8.5 upper values, and RCP8.5 median values + Antarctic Ice Sheet (AIS) for 2020, 2050, 2080, and 2100. Projections from the AR6 were obtained from the NASA Sea Level Projection Tool, which allows users to view sea level projections. The projections included in this study from the AR6 was SSP8.5 for 2020, 2050, 2080, 2100, and 2150.

Tables of extreme water levels were developed for each coastal zone. There were four tables developed per coastal zone (one for each SLR projection), resulting in a total of 20 extreme water level tables (5 coastal HRM zones X 4 SLR projections). An example of a table developed for Zone 1 under the RCP8.5 scenario is shown in Table i.

Table i: Zone 1, RCP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS
LLWLT	-1.46	-1.22	-0.93	-0.71	-0.06
MWL	-0.27	-0.03	0.26	0.48	1.13
HHWLT	0.93	1.17	1.46	1.68	2.33
2-Year RP	1.52	1.76	2.05	2.27	2.92
5-Year RP	1.53	1.77	2.06	2.28	2.93
10-Year RP	1.62	1.86	2.15	2.37	3.02
20-Year RP	1.71	1.95	2.24	2.46	3.11
50-Year RP	1.77	2.01	2.30	2.52	3.17
100-Year RP	1.82	2.06	2.35	2.57	3.22

Recommendations were provided in the report on how to determine the appropriate extreme water level for a specific project. Some of the main recommendations include considering the design life of the infrastructure, the risk tolerance to flooding, the surrounding infrastructure, and the ability for incremental raising (or other flooding mitigation measures). For long-term adaptation strategies, it is recommended to develop a design envelope to use as a guide and for general planning purposes. This could include developing an intermediate scenario (RCP8.5 or SSP8.5 median values) for short-term and medium-term planning and an upper-bound scenario (RCP8.5 + AIS or RCP8.5 upper values) for long-term planning and for infrastructure with very low flood-risk tolerance.

There are several limitations to this study which should be fully understood before using the extreme water levels provided in this report. Extreme water levels are appropriate only for sites in open coasts due to the potential amplification of storm surge that can occur in inlets, bays, etc. and with complex near-shore bathymetry. In addition, the extreme static water levels listed in this study only include the impacts of tides, storm surges, and sea level rise. Increased water levels due to waves and storm water runoff are not included. Site specific studies are recommended to determine the impacts of these parameters on extreme water levels.

Sea level rise projections are expected to evolve in the future as climate modelling progresses, and as emissions scenarios are recalibrated to the evolving global socioeconomic conditions. Extreme water levels should be regularly updated as new information becomes available.

Contents

Appendices

List of Acronyms

AIS	Antarctic Ice Sheet
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
BIO	Bedford Institute of Oceanography
CAN-EWLAT	Canadian Extreme Water Level Adaptation Tool
CGVD2013	Canadian Geodetic Vertical Datum of 2013
CHS	Canadian Hydrographic Service
DFO	Department of Fisheries and Oceans
HRM	Halifax Regional Municipality
HHWLT	Higher High Water Large Tide
IPCC	Intergovernmental Panel on Climate Change
LLWLT	Lower Low Water Large Tide
MWL	Mean Water Level
RCP	Representative Concentration Pathways
RP	Return Period
RSLR	Relative Sea Level Rise
SLR	Sea Level Rise
SSP	Shared Socioeconomic Pathway

Glossary

Higher High Water Large Tide – The average of the annual maximum tidal levels, 1 from each of 19 years of tidal predictions[2].

Lower Low Water Large Tide – The average of the annual minimum tidal level, 1 from each of 19 years of tidal predictions.

Mean Water Level – The average of all hourly water levels over the available period of record.

Return Period – The return period represents the average time interval between exceedances of a given threshold. It is also equivalent to the inverse of the frequency of occurrence. For example, a 100-year return storm surge has a 1/100 or 1% chance of being exceeded once in a year.

Sea Level Rise – Sea level rise is an increase in the ocean's water levels due to the effects of climate change. Global Mean SLR is caused primarily by two factors: (1) expansion of water from increasing ocean temperatures, and (2) the melting of polar ice sheets and mountain glaciers. Global Mean SLR will accelerate due to climate change, causing increased risks of coastal erosion and flooding. Relative sea level rise (RSLR) represents Global Mean SLR corrected with local factors including but not limited to vertical land motion, or changes in local oceanic circulation.

Storm Surge – Storm surges are created by meteorological effects on sea level, such as wind set-up (shoreward wind stresses causing an increase in water level) and low atmospheric pressure. Storm surge can be defined as the difference between the observed water level during a storm and the predicted astronomical tide. Regional storm surge trends can be inferred from large-scale models and nearby tide gauge observations if available.

Tide – Tides are the periodic rise and fall of the surface of oceans, bays, etc., due principally to the gravitational interactions between the moon, sun, and earth. The characteristics of tides such as amplitude and frequency vary depending on a variety of factors including but not limited to geographical position, dimensions, and depth of the body of water.

[2] Source: https://www.tides.gc.ca/en/definitions-content-tides-and-currents - Accessed 25 Apr 2022

1 Introduction

1.1 Context

Sea levels have been rising globally and are projected to continue to rise due to climate change. Paired with extreme storm events, coastal flooding can result in significant damage to coastal infrastructure. Defining extreme water levels is critical for coastal hazard assessments, coastal planning, policy development, the design of infrastructure, and ecosystem management. Halifax Regional Municipality (HRM) commissioned CBCL Limited (CBCL) to complete the present study to determine extreme static water levels for the region.

The objectives of the study were to first conduct a desktop review of extreme static water levels for the coastal zones of HRM due to the combined effects of tides, storm surges, and sea level rise. This would ultimately result in the production of a summarized document of the extreme water levels, which can be used by decision makers, planners, and consultants to determine potential coastal flooding hazards. The document includes tables of extreme water levels that are easy-to-read for a given return-period (RP) storm and sea level rise projection. This document also provides the definition of extreme water level components, recommendations on which extreme water levels to use, how to incorporate extreme water levels into the planning of a project, and limitations of the study.

1.2 Document Outline

After an extensive literature review and analysis of available water level data, tables of extreme water levels were developed for each of the specified zones throughout HRM. These coastal zones were based on areas of similar coastal conditions and extreme water levels.

The extreme static water levels include the following contributions:

- Tidal elevations for HHWLT, MWL, and LLWLT.
- Regional storm surges for 2-, 5-, 10-, 20-, 50-, 100-, 200-, 500-, and 1000-year RP storms whenever available.
- Sea level rise (SLR) for 2020, 2050, 2080, 2100, and 2150 for RCP4.5, RCP8.5, RCP8.5 upper values, RCP8.5 plus AIS, and SSP8.5 whenever available.

The derivation of the coastal zones in HRM are described in Chapter 2 . The definition, methodology, and results for tidal elevations, storm surge, and SLR values are described in

Chapters 3 4 and 5 respectively. Chapter 6 describes the keys findings of the study, recommendations on how to apply the results, and the limitations of the study.

Appendix A includes the tables of extreme water levels for each of the coastal zones of Appendix B includes a description of the statistical methodology used to calculate extreme water levels using long-term tide gauge data. Appendix C includes the sea level rise projections for all scenarios. Appendix D includes further information on how SLR was added to the tidal elevations.

1.3 Coastal Flooding Definitions

Coastal flooding is governed by the combination of:

- **Still water levels** from tide, storm surge, and SLR as defined in the present section.
- **Wave impacts**, including wave run up, wave setup, and overtopping components for areas exposed to waves.
- **Stormwater** ponding from runoff and overflows in extreme rainfall.
- **River** contribution for estuaries.

Extreme static water levels include contributions from the following parameters (Figure 1-1):

- **Tide** – Tides are the periodic rise and fall of the surface of oceans, bays, etc., due principally to the gravitational interactions between the moon, sun, and earth. The characteristics of tides such as amplitude and frequency vary depending on a variety of factors including but not limited to geographical position, dimensions, and depth of the body of water.
- **Storm Surge** – Storm surges are created by meteorological effects on sea level, such as wind set-up (shoreward wind stresses causing an increase in water level) and low atmospheric pressure. Storm surge can be defined as the difference between the observed water level during a storm and the predicted astronomical tide. Regional storm surge trends can be inferred from large-scale models and nearby tide gauge observations if available.
- **Sea Level Rise (SLR)** – SLR is an increase in the ocean's water levels due to the effects of climate change. Global Mean SLR is caused primarily by two factors: (1) expansion of water from increasing ocean temperatures, and (2) the melting of polar ice sheets and mountain glaciers. Global Mean SLR will accelerate due to climate change, causing increased risks of coastal erosion and flooding. Relative sea level rise (RSLR) represents Global Mean SLR corrected with local factors including but not limited to vertical land motion, or changes in local oceanic circulation.

This study provides extreme static water levels for HRM. Wave impacts, stormwater inputs, and river contributions are not included in the extreme water levels provided in this document. These parameters are generally site specific and therefore, a detailed study would be required for the specified site to determine these contributions.

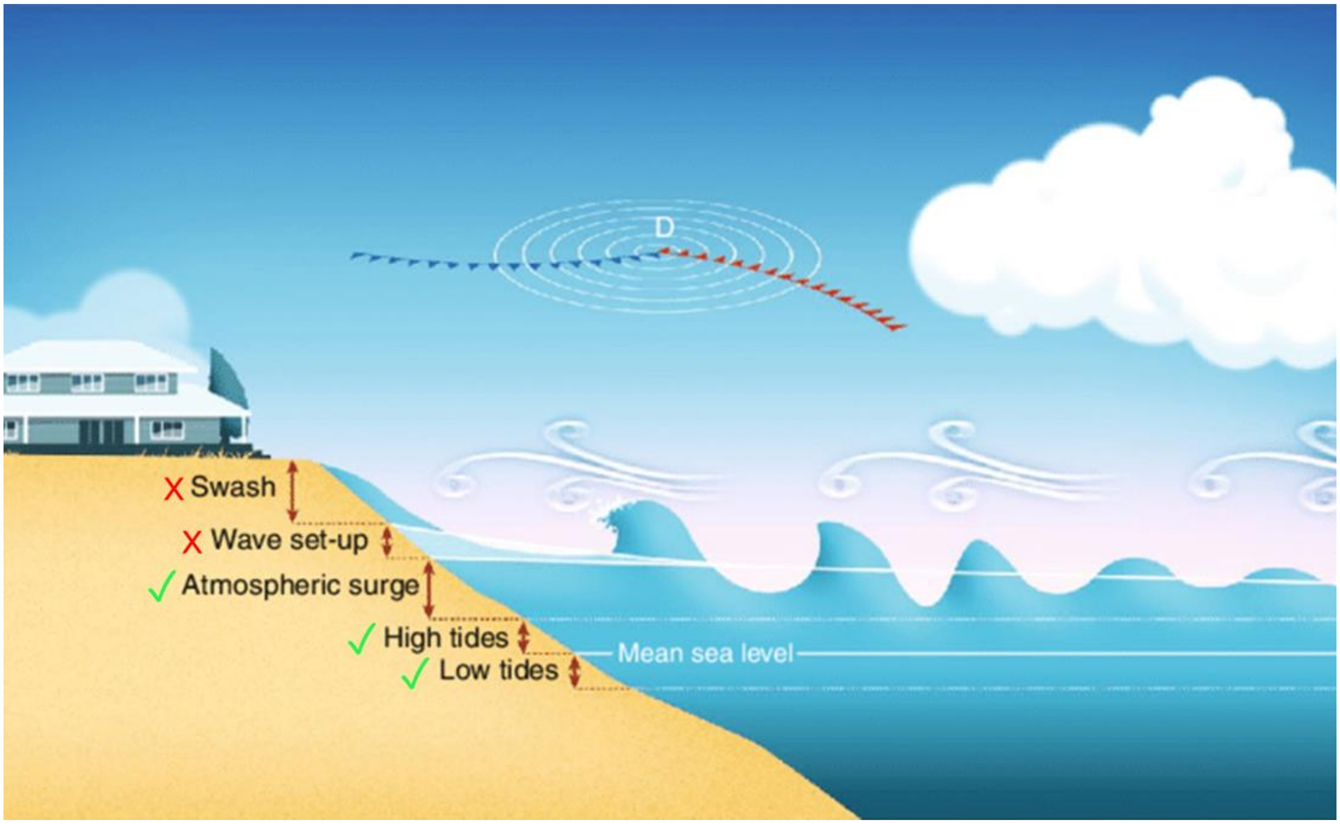

Figure 1-1: Components of extreme total water levels and extreme static water levels (figure adapted from Melet *et al.*, 2018). Green check marks indicate components included in extreme static water levels for this study and red X's indicate extreme water level components not included in extreme static water levels for this study.

2 Coastal Zones

Five coastal zones were developed for this report, which were based on areas of similar coastal conditions. The zones were established by comparing the HHWLT and storm surge values across HRM and grouping these areas together based on similar extreme water levels. Extreme water levels for each of the coastal zones are presented in Appendix A. The five coastal zones include (Figure 2-1):

- **Zone 1 –** St. Margaret's Bay.
- **Zone 2 –** Peggy's Cove, Terence Bay, Sambro.
- **Zone 3 –** Bedford, Halifax, Dartmouth, Eastern Passage.
- **Zone 4 –** Lawrencetown, Seaforth, Chezzetcook.
- **Zone 5 –** Clam Harbour, Tangier, Sheet Harbour.

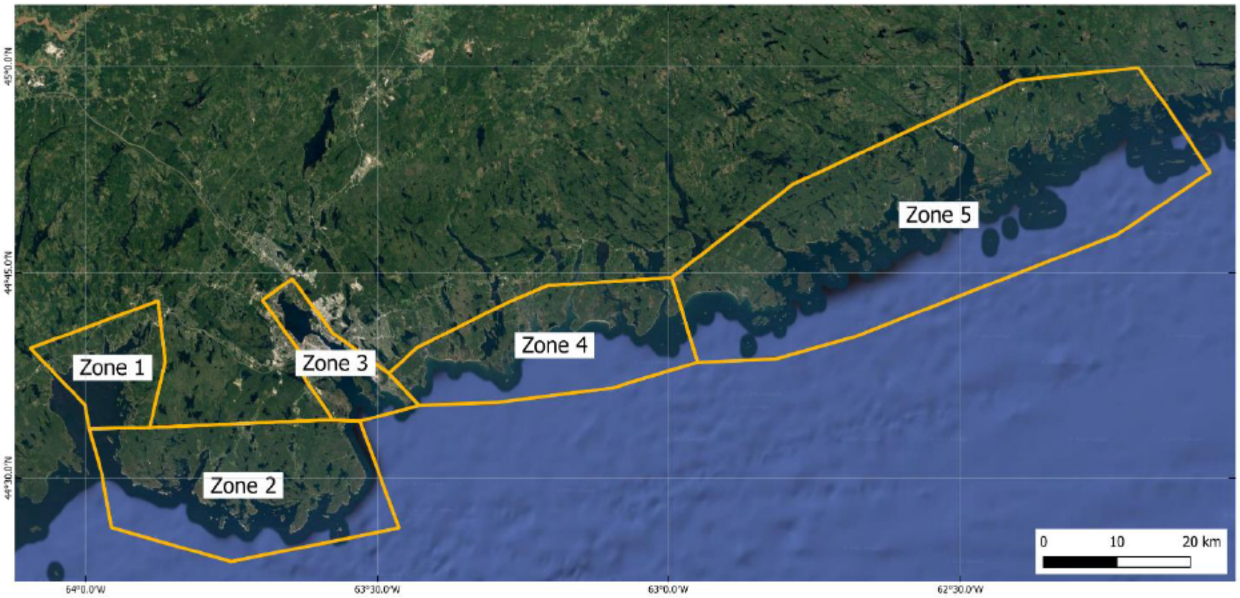

Figure 2-1: Five coastal zones established for HRM extreme water levels.

3 Tidal Elevations

3.1 Definitions

Tides are the periodic rise and fall of the surface of oceans, bays, etc., due principally to the gravitational interactions between the moon, sun, and earth. The characteristics of tides can vary globally including the frequency of tidal oscillations. In HRM, tides are *semidiurnal*, which means two high and two low tides in a lunar day. Tides can also vary in amplitude with differing tidal ranges, which is the difference in low tide and high tide. Tides generated in the ocean propagate inland onto the continental shelf where amplification (an increase of tidal range) can occur. Various characteristics can impact amplification including depth of the shelf, shoaling due to increased bed friction, and funneling due to the reduced width of an area. Tidal ranges can also be further altered when entering inlets and estuaries due to the shallow depth of the system.

The analysis of tidal elevations in HRM focused on the three tidal elevations including Higher High Water Level Large Tide (HHWLT), Mean Water Level (MWL), Lower Low Water Large Tide (LLWLT). The definitions of these water levels include:

- HHWLT – The average of the annual maximum tidal levels, 1 from each of 19 years of tidal predictions.
- MWL – The average of all hourly water levels over the available period of record.
- LLWLT – The average of the annual minimum tidal level, 1 from each of 19 years of tidal predictions.

3.2 Methodology

Two data sources were used to analyze these tidal elevations throughout HRM. The first being the Canadian Tide and Current Tables (Canadian Hydrographic Service – Department of Fisheries and Oceans, 2022). The second source of tidal elevations was the Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT) (Bedford Institute of Oceanography, 2016).

The Canadian Tide and Current Tables was developed by the Canadian Hydrographic Service (CHS), which is part of the Department of Fisheries & Oceans (DFO). The tide tables are provided for reference ports and secondary ports each year. Within HRM, Halifax is a reference port and there are several secondary ports. Tidal elevations for all ports are presented in the tide tables, however, it has been noted by CHS that tidal elevations at reference ports are typically more accurate because tidal elevations are usually based on at least one year of data whereas data for secondary ports is limited (in most cases data does not extend over more than one month). CHS states the accuracy of the water levels is dependent on the similarity between the characteristics of the tide at the secondary and reference ports. Efforts by CHS have been made to compare reference and secondary ports which have similar tidal characteristics, but because of the relatively small number of reference ports available this has not always been possible. However, the inaccuracies are usually less than fluctuations in the total water levels due to meteorological conditions.

The Bedford Institute of Oceanography (BIO) developed the online Canadian CAN-EWLAT application. This tool was developed primarily for DFO Small Craft Harbours (SCHs) but can be used by coastal planners for infrastructure along Canada's coast (Greenan & Perrie, 2021). The tidal elevations where tide gauge data is available is derived from measured data. At small craft harbour sites where measured data is not available, elevations are determined using a combination of water level observations and modelled tides between observation sites. CAN-EWLAT states that potential average inaccuracies for sites can be approximately +/- 10 to 20 cm, however, inaccuracies may be larger for areas with limited observations.

The tidal elevations were collected for all the available ports and SCHs in HRM. A quality check of the tidal elevations was first completed to ensure that the elevations were a reasonable value for the area. The tidal elevations were then sorted by the coastal zones assigned in this report. The maximum HHWLT in each zone was used to ensure that the extreme water level derived for the zone was conservative. The corresponding tidal elevations to the port with the maximum HHWLT were used to maintain consistent tidal amplitudes. A list of all the ports analyzed is listed in Table 3-1, with the ports that were used in the final tidal elevations **bolded**.

In all cases except for Zone 1, the maximum HHWLT and the corresponding tidal elevations were used in each coastal zone[3].

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[3] The HHWLT listed in the DFO tide tables for Hubbards exceeds the maximum high tide in Zone 1. CBCL conducted a background analysis of the local archived water level observations across St Margarets Bay. The review raised potential discrepancies on the vertical reference level across the record, and indicated the observed tidal range to be similar across all local stations (including Hubbards). Therefore, the listed tidal elevations from Hubbards were not used.

Table 3-1: List of ports used to assess the tidal elevations in HRM including the source and corresponding coastal zone. Ports highlighted in bold were used as the tidal elevation for the specified coastal zone.

Ports Locations	Source	Zone
Middle Point Cove	CAN-EWLAT	2
Peggy's Cove	CAN-EWLAT	2
West Dover	CAN-EWLAT	2
East Dover	CAN-EWLAT	2
Shad Bay	CAN-EWLAT	2
Terence Bay	CAN-EWLAT	2
Lower Prospect	CAN-EWLAT	2
Sambro	CAN-EWLAT	2
Portugese Cove	**CAN-EWLAT**	**2**
Eastern Passage	CAN-EWLAT	3
Three Fathom Harbour	**CAN-EWLAT**	**4**
East Chezzetcook	CAN-EWLAT	4
Little Harbour	CAN-EWLAT	5
Owls Head	CAN-EWLAT	5
Carters Point	CAN-EWLAT	5
Coopers Point	CAN-EWLAT	5
Gammons Creek	**CAN-EWLAT**	**5**
Hubbards	CHS	1
Mill Cove	**CHS**	**1**
Boutiliers Point	CHS	1
Indian Harbour	CHS	2
Prospect	CHS	2
Sambro Harbour	CHS	2
Bedford Institute of Oceanography (BIO)	**CHS**	**3**
Halifax	CHS	3
Three Fathom Harbour	CHS	4
East Chezzetcook	CHS	4
Sheet Harbour	CHS	5
Ecum Secum	CHS	5

3.3 Results

Tidal elevations for each coastal zone were derived based on an analysis of the Canadian Tide and Current Tables (CHS-DFO, 2022) and the CAN-EWLAT tool (BIO, 2016). The tidal elevations for each coastal zone are shown in Figure 3-1, which includes LLWLT, MWL, and HHWLT.

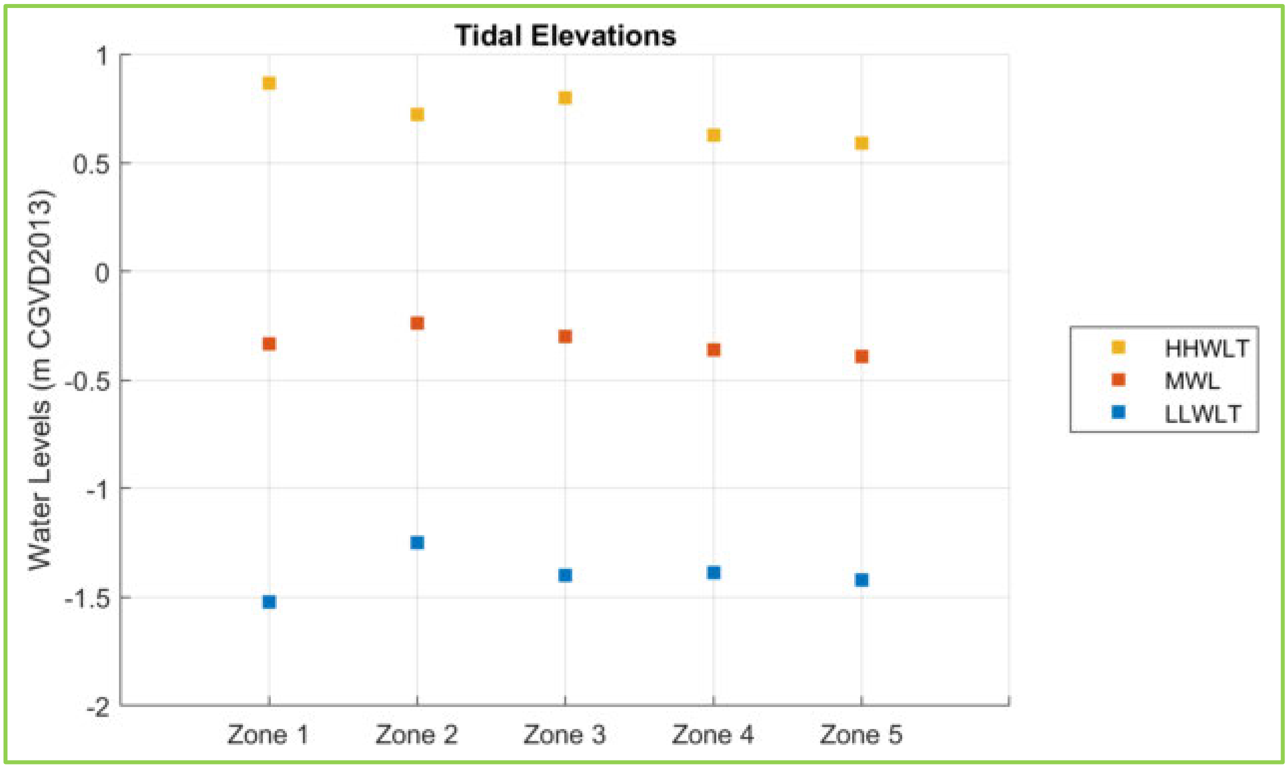

Figure 3-1: **Tidal elevations for each of the coastal zones.** Water levels are in CGVD2013.

4 Storm Surge

4.1 Definition

Storm surge is due to meteorological effects on sea level, such as wind set-up and low atmospheric pressure, and can be defined as the difference between the observed water level during a storm and the predicted astronomical tide. In areas exposed to breaking waves over a wide beach, wave setup represents an additional contribution to the storm surge. Wind set-up refers to the increase in mean water level along the coast due to shoreward wind stresses on the water surface. Wave set-up refers to the increase in mean water level along the coast due to shoreward stresses generated by breaking waves. Wave set-up can be a significant component of the surge along wide beaches with a large breaker zone.

4.2 Methodology

Two methods to determine storm surges in HRM were used depending on data availability. Ideally, to determine extreme water levels due to tides and surge (no SLR), long-term tide gauge data would be used. Long-term tide gauge data was only available at the BIO in the Bedford Basin (Zone 3). Therefore, extreme water levels were calculated for Zone 3 using an extreme value analysis of the total water level peaks measured by the BIO tide gauge after detrending for historical SLR. The chosen method based on total water level peaks ensures that the N-year extreme water level is statistically representative, accounting for the possibility that extreme storm surges do not always coincide with the highest tides. Further details describing this statistical methodology used to calculate extreme water levels are described in Appendix B.

Where tide gauge data was not available (Zone 1, 2, 4, and 5), an existing storm surge hindcast was used. Regional modeling of storm surge was conducted by Bernier & Thompson (2006), which developed a 40-year hindcast in the Northwest Atlantic. The aim of the study was to calculate the RP of extreme sea levels. Sample results shown in Figure 4-1 illustrate the large-scale spatial patterns of storm surge intensity across the region, not accounting for tides. The storm surge residual from this modeling study were used by Daigle (2020) who estimated the N-year return total water level (TWL) as follows:

TWL = HHWLT + N-year return storm surge residual

This methodology assumes that the peak storm surge coincides with the HHWLT. The limitations of this method are that due to coarse model resolution and the difficulty associated with modeling localized effects, storm surge may not be properly resolved in the nearshore particularly of harbours or bays. For example, the effect of wind setup on a harbour or the shape of a coastal inlet on storm surge amplification is not captured by the storm surge model.

The RPs for the extreme water levels due to tides and surge (no SLR) derived were 2-, 5-, 10-, 20-, 50-, and 100-year RP for all coastal zones. Higher RPs were calculated for Zone 3 including 200-, 500-, and 1000-year RP. These higher RP storm levels could not be calculated for Zones 1, 2, 4, and 5 because they were not included in the storm surge hindcast developed by Bernier & Thompson (2006). In addition, Bernier & Thompson (2006) did not provide storm surge residuals for a 20-year RP, however, a 25-year RP was included in their hindcast. Therefore, to derive the 20-year RP extreme water levels for Zones 1, 2, 4, and 5, the 25-year RP storm surge residual was used. This approach was deemed acceptable due to the similarity in surge levels of these two return periods, and because the difference between the 20-yr and 25-yr RP is less than the uncertainty associated with the derivation of the surge levels.

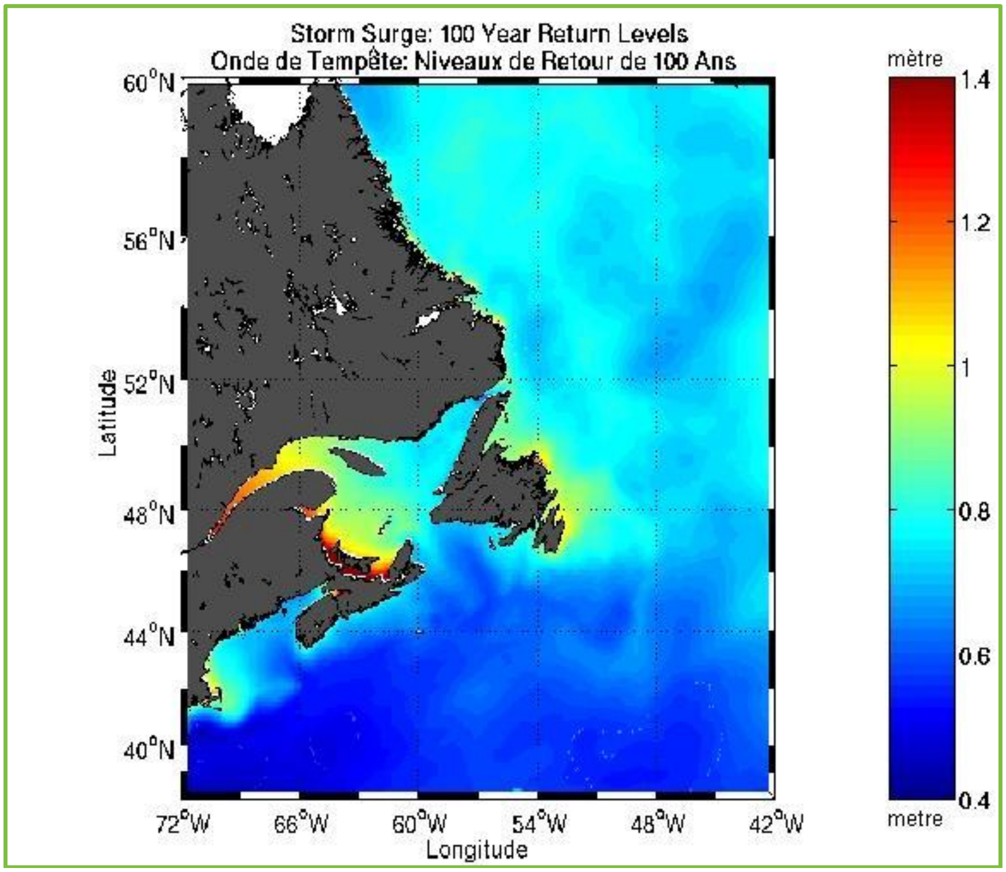

Figure 4-1: Extreme storm surge residual for a 100-Year RP across the Maritimes (Source: Bernier & Thompson, 2006).

4.3 Limitations

The limitations of the extreme water levels due to tides and surge (no SLR) derived by these methods are that storm surge can be amplified when approaching the shoreline. Due to site-specific parameters, such as near-shore bathymetry, narrowing inlets, or harbour layouts, storm surge amplification can occur, resulting in increased storm surge. For example, CBCL Limited recently completed a Metocean Conditions Assessment for the *Mill Cove Ferry Service Project* (2022) where detailed hydrodynamic modelling was performed. The extreme water levels due to tides and surge (no SLR) values were based on the extreme value analysis of the total water level peaks measured at the BIO tide gauge, as mentioned in Section 4.2. Mill Cove is located at the end of the Bedford Basin and because of this extreme storm surges tend to be larger than at the measuring location at the Narrows; therefore, an additional 0.1 m of surge was added to the Mill Cove extreme water levels (no SLR) for events with RPs larger than 20 years.

It is recommended that for a project site in a coastal inlet, estuary, bay, or harbour, a detailed study be conducted to determine the storm surge for that location.

4.4 Results

Extreme water levels due to tides and surge (no SLR) for each coastal zone were derived based on an analysis of long-term tide gauge in the Bedford Basin (BIO) for Zone 3 and the storm surge residuals calculated from Bernier & Thompson (2006) for Zone 1, 2, 4, and 5. These extreme water levels were derived for 2-, 5-, 10-, 20-, 50-, 100-year RP for all zones and additionally, 200-, 500-, and 1000-year RP for Zone 3, due to data availability. Extreme water levels (no SLR) and the tidal elevations for each coastal zone are shown in Figure 4-2.

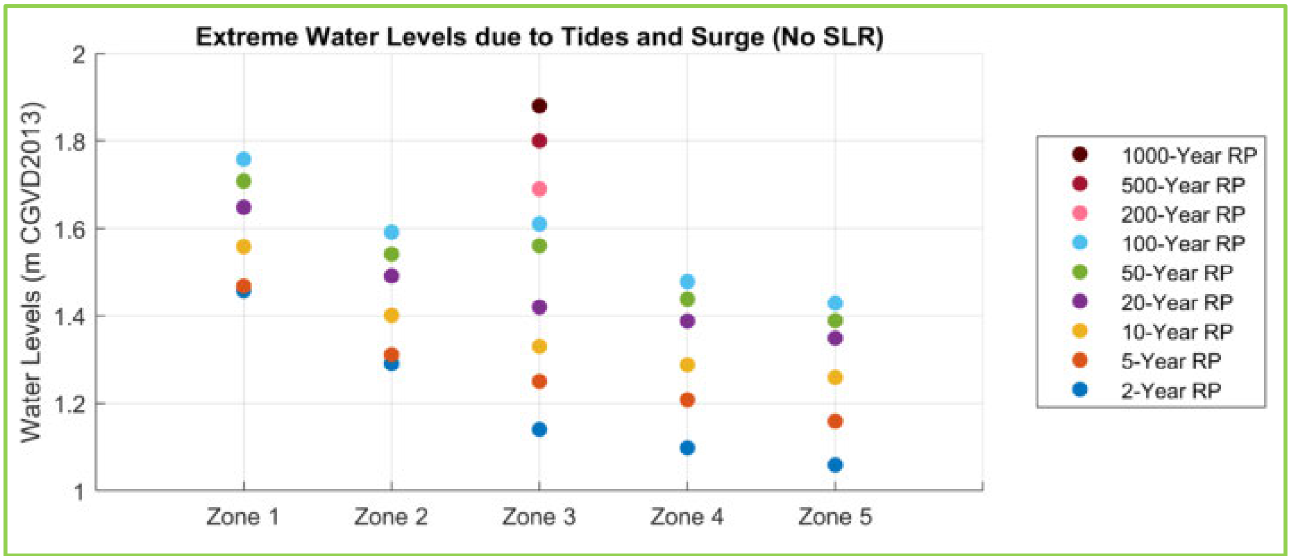

Figure 4-2: Extreme water levels due to tides and surge (no SLR) for each of the coastal zones for the various RPs. Water levels are in CGVD2013.

5 Sea Level Rise

5.1 Background

Sea levels have been rising in the Maritimes since the end of the last ice age 10,000 years ago. This trend is expected to accelerate with climate change due to the expansion of ocean waters and melting of glaciers due to increased temperatures. Due to rising sea levels, more frequent and severe flooding of coastal infrastructure will occur due to an upward shift in the tidal elevations and extreme water levels. SLR projections have been developed by the Intergovernmental Panel on Climate Change (IPCC) in 2013 and published in the Fifth Assessment Report (AR5) and in 2021 the Sixth Assessment Report (AR6) was published. These two reports are used for the SLR projections listed in this report for HRM. The IPCC is a scientific body of the United Nations responsible for advancing knowledge on climate change.

5.2 Methodology

5.2.1 Fifth Assessment Report (AR5)

In 2013, the IPCC developed the AR5, which contained projections of future climate change impacts, including SLR globally. The AR5 is the fifth series of reports developed by the IPCC. Several emission scenarios were described in these reports known as Representative Concentration Pathways (RCPs), which represent future changes in anthropogenic greenhouse gas emissions, including RCP4.5 and RCP8.5, which are the RCPs discussed in the present study. RCP4.5 represents a reduction in greenhouse gas emissions, whereas RCP8.5 represents a scenario where there is little to no reduction in emissions, often referred to as “business as usual”. Figure 5-1 illustrates the global SLR under the various RCP scenarios, with greatest SLR occurring under RCP8.5.

James *et al*. (2014) through the Natural Resources Canada (NRCAN) downscaled the AR5 global SLR values to generate regional projections for Canada. The regional aspects that James *et al*. (2014) included were vertical land motion, elastic crustal response due to ice-mass changes, and oceanographic changes due to climate change. Relative sea-level change across Canada for 2006 and every decade from 2010 to 2100 was calculated. James *et al*. (2021) further built on the previous report to provide geospatial data files (geoTIFFs) of projected SLR across Canada, which is what was used in this study to derive SLR across HRM.

An additional scenario was also developed by James *et al*. (2014), referred to in this report as RCP8.5 + AIS (Antarctic Ice Sheet). This scenario is based on the instability of the West

Antarctic Ice Sheet (WAIS). There is potential for the rapid collapse of the WAIS due to climate change, which would further contribute to SLR. It was proposed at the time to add an additional 0.65 m by 2100 of Global Mean SLR to RCP8.5, which would take into account the contribution of the WAIS collapse. This scenario is intended to be used if the tolerance to risk of sea-level rise is very low, due to the low confidence of this scenario.

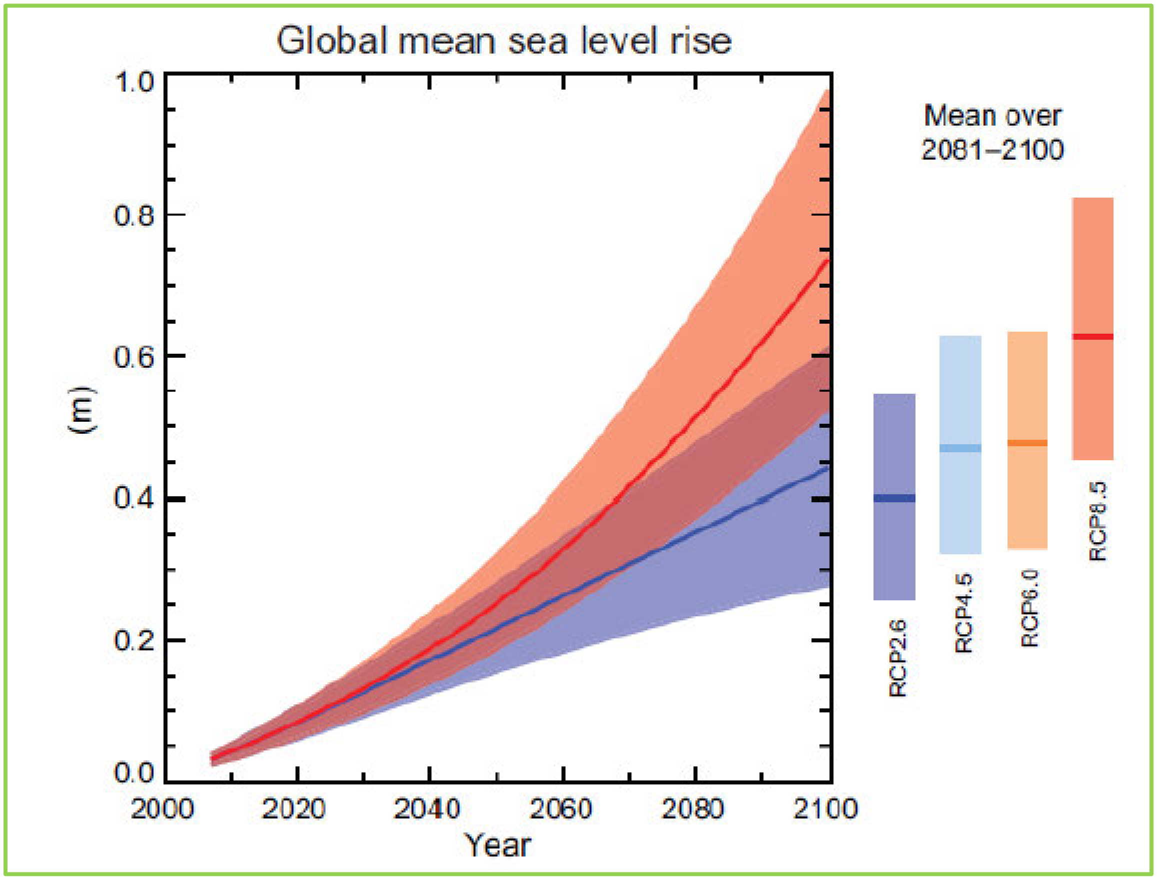

Figure 5-1: Projections of sea level rise presented within the AR5 (Source: IPCC. 2014. Climate Change 2014: Synthesis Report).

5.2.2 Sixth Assesment Report (AR6)

The most recent report IPCC was released in 2021, which is the AR6. This report provides further updated climate change projections including SLR. The IPCC AR6 report applied a new scenario framework in order to incorporate a combined analysis of future climate change impacts in terms of socioeconomics, vulnerabilities, and adaptation (Riahi *et al.*, 2017). The new scenarios are referred to as Shared Socioeconomic Pathways (SSPs) and vary based on socio-economic development, land use, demographics, etc. Some of the scenarios include SSP1-2.6 (low emission scenario), SSP2-4.5 (intermediate emission scenario), SSP3-7.0 (high emission scenario), and SSP5-8.5 (very high emission scenario). SSP8.5 will be the scenario included in the SLR projections from AR6 in this report.

NASA released the NASA Sea Level Projection Tool (Fox-Kemper *et al.*, 2021), which allows users to view and download sea level projections calculated by the AR6. The tool includes a data point for Halifax, which was used for the SSP8.5 SLR projection in HRM. The projections are not regionally downscaled from the AR6 report, however, the model used for these projections are from the North Atlantic Ocean model. Since there was only one data point in Halifax all SLR values for the SSP8.5 scenario for each of the coastal zones are the same.

A low-confidence scenario for the SSP5-8.5 was developed in the AR6, which incorporates a representation of the potential melting of ice sheets. Currently, only a range is provided for this scenario, due to the recent release of the AR6 report. The addition of 0.65 m to Global Mean SLR for AR5 RCP8.5 in 2100 due to the potential collapse of the WAIS, was developed by James *et al.* (2014) and based on several sources of literature and in-depth analysis. Due to the purpose of this study and since a recommended SLR value due to ice sheet processes has not been developed at this time for AR6, the low confidence scenario for SSP8.5 was not included in this study. It is recommended to revisit the addition of the low confidence scenario to the extreme water levels for HRM in the future when further studies have been conducted.

5.2.3 Summary

In summary, the five various SLR projections were used in this analysis include:

- RCP4.5 median values
- RCP8.5 median values
- RCP8.5 upper values (95th percentile)
- RCP8.5 median values + AIS
- SSP8.5 median values

Two sources of SLR projections were used for this analysis which include:

- IPCC AR5 for RCP4.5 and RCP8.5 (+AIS) produced by NRCAN (James *et al.*, 2021).
- IPCC AR6 for SSP8.5 produced by NASA's Sea Level Projection Tool (Fox-Kemper *et al.*, 2021).

5.3 Results

SLR projections for each coastal zone were derived for RCP4.5 median values, RCP8.5 median values, RCP8.5 upper values (95th percentile), RCP8.5 median values + AIS, and SSP8.5 median values for 2020, 2050, 2080, 2100, and 2150 where available. An example of the SLR projections for Zone 1 is illustrated in Figure 5-2. The SLR projections for all coastal zones in HRM are shown in Appendix C

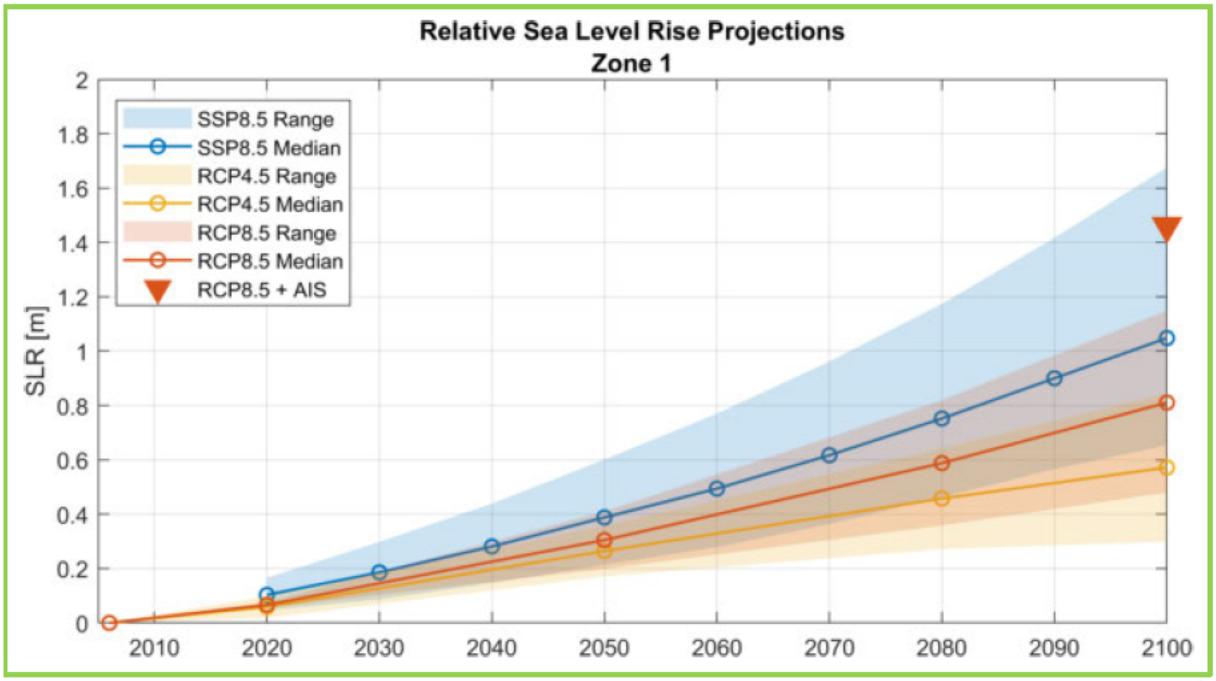

Figure 5-2: Sea Level Rise Projections for Zone 1 for the Various Scenarios. The 5th and 95th percentiles are the shaded lower and upper limits, while the solid line is the median projection. The inverted triangle represents RCP8.5 + AIS in 2100.

5.4 Recommendations

The appropriate scenario to use depends on the application, such as the planning time horizon or risk tolerance of the area and infrastructure assets. Sites with low risk tolerance or long-term planning time horizons should use conservative SLR projections such as RCP8.5 upper values or RCP8.5 + AIS. Sites with tolerance for occasional flooding, short- to medium-term planning time horizons, or the possibility for incremental raising can apply an intermediate SLR projections such as RCP8.5 or SSP8.5 median values. For general planning purposes, the following approach using two scenarios to develop an envelope can also be considered, as per NOAA's recommendations (Sweet *et al.*, 2017):

- Define an ***intermediate* scenario** for short-term and medium-term planning. We propose that this scenario use projections up to RCP8.5 or SSP8.5 median values. This intermediate scenario may be used for defining the elevation of coastal protection structures and potentially roads, which could be built for a shorter design life and/or have built-in flexibility to allow incremental raising.
- Define an ***upper-bound* scenario**, which in the present case could be the extreme SLR projection (RCP8.5 + AIS) and use it as a guide for overall risk and long-term adaptation strategy. The upper-bound scenario can be used for guiding the selection of minimum site elevations required for siting of future and potentially vulnerable permanent infrastructure.

6 Conclusion

6.1 Key Findings

Flooding scenarios are presented in this document for 5 coastal zones in HRM for extreme static water levels. The coastal zones were based on coastlines that have similar coastal conditions, including tidal elevations, storm surge, and SLR. Tables that include SLR projections and various storm levels were calculated for each coastal zone so that extreme static water levels can be easily identified. A table was calculated for each SLR projection (RCP4.5 median values, RCP8.5 median and upper values, and SSP8.5 median values). Within each table, the RP storms that were included were 2-, 5-, 10-, 20-, 50- and 100-Year and additionally, 200-, 500-, and 1000-Year for Zone 3. An example of a table developed for Zone 1 under the RCP8.5 scenario is shown in Table 6-1. Four tables were developed for each coastal zone, resulting in a total of 20 extreme water level tables (5 coastal HRM zones X 4 SLR projections). Tables for all coastal zones are presented in Appendix A.

The following items provide recommendations on how to select the appropriate extreme water levels for the site or project considered:

- When choosing a storm RP for design elevations, it is often recommended to use a RP of 100-years. For temporary infrastructure, the RP could be adjusted to meet the importance of the infrastructure and taking into consideration the maintenance cost and consequence of flooding. Similarly, for more critical infrastructure that needs to be fully operational during extreme storms, the definition of the RP might have to be higher (e.g., 500 to 1000-years).
- Climate change will result in more frequent flooding of coastal infrastructure due to an upward shift in the tidal elevations and extreme water levels due to rising sea levels.
- An appropriate planning period should be selected for the project to evaluate SLR impacts. Many projects use 2100 as the end point, however, a shorter time period can be selected for temporary infrastructure or infrastructure that can be incrementally raised. For example, if a structure is being constructed in 2030 and has a design life of 50 years, 2080 could be selected as the project end point. Conversely, for projects with a design life greater than 80 years, a time horizon beyond 2100 should be considered.
- When choosing the SLR projection for specific infrastructure, it is important to consider the risk tolerance and design life of the infrastructure. For structures that are not permanent or have the flexibility to allow for incremental raising, scenarios RCP8.5 or SSP8.5 median values should be considered. For the design of critical or vulnerable infrastructure, extreme SLR projections should be considered, such as RCP8.5 upper values or RCP8.5 + AIS.

- For the general planning of a coastal area, an envelope could be considered as detailed in Section 5.4 (Sweet *et al.*, 2017). This would include defining an *intermediate* scenario for short-term and medium-term planning, which is recommended to be RCP8.5 or SSP8.5 median values. This intermediate scenario may be used for defining the elevation of coastal protection structures and potentially roads, which could be built for a shorter design life or allow for incremental raising. The *upper-bound* scenario, which in the present case could be the extreme SLR projection that includes RCP8.5 + AIS. This could be used as a guide for overall risk and long-term adaptation strategy and for the siting of vulnerable or permanent infrastructure.
- For the design of coastal infrastructure in bays, inlets, or harbours, a detailed study to determine the storm surge (and potential storm water runoff or fluvial driven flooding) for that location is recommended. Amplification of storm surge can occur due to shallow near-shore bathymetry, narrowing inlets, or harbour layouts, which would require a more detailed investigation to determine.
- The science of SLR will continue to evolve with updated observations and improved model predictions. Implications for infrastructure and coastal flooding will need to be re-evaluated with periodic updates in SLR projections.

Table 6-1: Zone 1 (St. Margaret's Bay), RCP8.5 sea level rise scenario (median values). Water Levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS
LLWLT	-1.46	-1.22	-0.93	-0.71	-0.06
MWL	-0.27	-0.03	0.26	0.48	1.13
HHWLT	0.93	1.17	1.46	1.68	2.33
2-Year RP	1.52	1.76	2.05	2.27	2.92
5-Year RP	1.53	1.77	2.06	2.28	2.93
10-Year RP	1.62	1.86	2.15	2.37	3.02
20-Year RP	1.71	1.95	2.24	2.46	3.11
50-Year RP	1.77	2.01	2.30	2.52	3.17
100-Year RP	1.82	2.06	2.35	2.57	3.22

6.2 Limitations

Tidal elevations were sourced from CHS and CAN-EWLAT ports. Elevations from CHS, excluding at Halifax (Zone 3), are from secondary ports. CHS states that there is limited data available to calculate the tidal elevations (in most cases does not extend over one month). Therefore, the accuracy of tidal elevations provided by CHS may slightly vary due the limited data available. However, CHS states that inaccuracies created are usually less than those caused by fluctuations in the tide levels due to meteorological conditions. Similarly, CAN-EWLAT states that potential inaccuracies are possible at the various sites due to limited data available for the calculation of tidal elevations. CAN-EWLAT states that potential average inaccuracies for both sites can be approximately +/- 10 to 20 cm

Storm surge values were derived using long-term tide gauge data where possible, however, long-term tide gauge data was only available in the Bedford Basin. Therefore, storm surge values for Zones 1, 2, 4, and 5 were based on a storm surge hindcast developed by Bernier & Thompson (2006). The hindcast is limited to offshore locations and therefore, storm surge could be underestimated in locations where surge can be amplified such as inlets, bays, estuaries, and harbours. It is recommended that for a project site in locations with the above characteristics, a detailed study be conducted to determine the storm surge for that location.

There are uncertainties relating to SLR projections due to modelling capabilities in addition to the unknowns surrounding future anthropogenic emissions. There is relatively small uncertainty for SLR up to 2050, however, there is less certainty on SLR values after 2050. There is particular uncertainty regarding the collapse of the West Antarctic Ice sheet, which is currently being described as a low confidence scenario. SLR projections should be regularly reviewed and updated based on the latest climate change science to continually improve SLR values in this report, particularly when new information/ regional SLR projections of AR6 are available for Halifax.

The extreme static water levels derived in this report only include the combination of tides, storm surges, and SLR. Increased water levels due to wave setup, wave run-up, storm water runoff, and fluvial contributions are not included in the extreme water levels provided in this report. If a site is exposed to wave action, storm water runoff, or fluvial contribution, a site-specific study is recommended to determine the impacts to extreme water levels. These values could not be included in this study as they are site specific and dependant on several factors.

Results should be interpreted with caution and actual conditions encountered in the future may vary from predictions. For selecting design floor elevations of critical infrastructure, structures with low tolerance to flooding, or permanent coastal structures, it is recommended that detailed coastal studies be performed. We also recommend that results be revisited regularly as new information becomes available (i.e. SLR projections, water level measurements, tidal elevations, etc.).

6.3 Closing

This report presents extreme static water levels for five coastal zones in HRM. These water levels are due to the combined effects of tides, storm surge, and sea level rise. This report has been prepared based on a specific scope of work, and it should be read in its entirety. The findings and recommendations are based on information collected to date at the time of writing. Results should regularly be revisited and updated when more information becomes available. The limitations of the extreme water level values should be considered for all uses.

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7 References

Bedford Institute of Oceanography – Department of Fisheries and Oceans. (2016). Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT). https://www.bio.gc.ca/science/data-donnees/can-ewlat/index3-en.php

Bernier, N.B., Thompson, K.R. (2006). Predicting the frequency of storm surges and extreme sea levels in the northwest Atlantic. J. Geophys. Research Vol 111 C10009.

Canadian Hydrographic Service – Department of Fisheries and Oceans. (2022). Canadian Tide and Current Tables. Canadian Tide and Current Tables. https://charts.gc.ca/publications/tables-eng.html

Daigle, R. (2020). Updated Sea-Level Rise and Flooding Estimates for New Brunswick Coastal Sections 2020 - Based on IPCC 5th Assessment Report. Prepared for New Brunswick Department of Environment and Local Government.

Fox-Kemper, B., H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J-B. Sallée, A. B. A. Slangen, Y. Yu. (2021). Ocean, Cryosphere and Sea Level Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [MassonDelmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

Greenan, B., & Perrie, W. (2021). Canadian extreme water level adaptation tool (can-EWLAT). Bedford Institute of Oceanography. Retrieved February, 2022, from https://www.bio.gc.ca/science/data-donnees/can-ewlat/index-en.php

IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

James, T.S., Henton, J. A., Leonard, L. J., Darlington, A., Forbes, D. L., Craymer, M. (2014). Relative sea-level projections in Canada and the adjacent mainland United States; Geological Survey of Canada, Open file 7737, 72pp. https://doi.org/10.4095/295574

James, T.S., Henton, J.A., Robin C., Craymer, M. (2021). Relative sea-level projections for Canada based on the IPCC Fifth Assessment Report and the NAD83v70VG national crustal velocity model; Geological Survey of Canada, Open file 8764, 23pp. https://doi.org/10.4095/327878

Melet, A., Meyssignac, B., Almar, R., & Le Cozannet, G. (2018). Under-estimated wave contribution to coastal sea-level rise. Nature Climate Change, 8(3), 234–239. https://doi.org/10.1038/s41558-018-0088-y

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Crespo Cuaresma, J., Samir, K. C., Leimback, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M. (2016). Shared socioeconomic pathways: an overview. Global Environment. doi: http://dx.doi.org/10.1016/j.gloenvcha.2016.05.009.

Robin, C., Nudds, S., MacAulay, P., Godin, A., Boom, B., Bartlett, J. (2016). Hydrographic Vertical Separation Surfaces (HyVSEPs) for the Tidal Waters of Canada. Marine Geodesy, 39:2, 195-222, DOI: 10.1080/01490419.2016.1160011

Sweet, W.V., Kopp, R.E., Weaver, C.P., Obeysekera, J., Horton, R.M., Thieler, E.R., Zervas, C. (2017). NOAA Technical Report NOS CO -OPS 083: Global and Regional Sea Level Rise Scenarios for the United States. Silver Spring, Maryland.

APPENDIX A

Extreme Water Level Tables

Median and upper values are provided for time horizons 2020, 2050, 2080, 2100 and 2150 for various scenarios at each coastal zone (Figure A- 1). Certain scenarios do not have available projections beyond year 2100, which is shown as a N/A entry. For typical confidence intervals in the SLR projections, please see Appendix C.

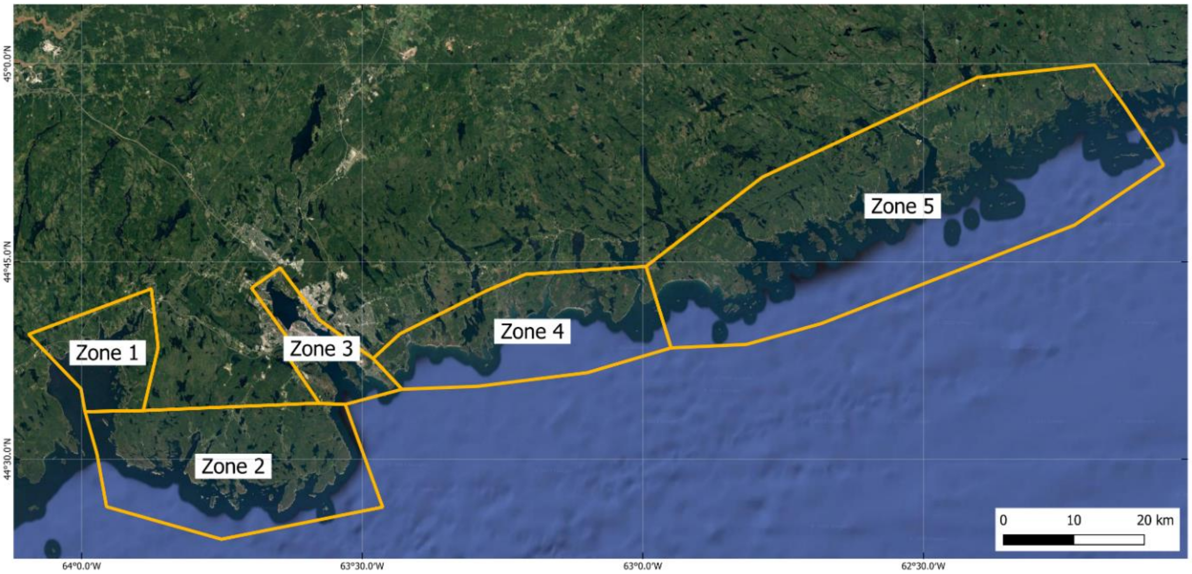

Figure A- 1: Five coastal zones established for HRM extreme water levels.

Zone 1: St Margaret's Bay

Table A- 1: Zone 1, RCP4.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.46	-1.26	-1.06	-0.95	N/A	N/A
MWL	-0.27	-0.07	0.13	0.24	N/A	N/A
HHWLT	0.93	1.13	1.33	1.44	N/A	N/A
2-Year RP	1.52	1.72	1.92	2.03	N/A	N/A
5-Year RP	1.53	1.73	1.93	2.04	N/A	N/A
10-Year RP	1.62	1.82	2.02	2.13	N/A	N/A
20-Year RP	1.71	1.91	2.11	2.22	N/A	N/A
50-Year RP	1.77	1.97	2.17	2.28	N/A	N/A
100-Year RP	1.82	2.02	2.22	2.33	N/A	N/A

Table A- 2: Zone 1, RCP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.46	-1.22	-0.93	-0.71	-0.06	N/A
MWL	-0.27	-0.03	0.26	0.48	1.13	N/A
HHWLT	0.93	1.17	1.46	1.68	2.33	N/A
2-Year RP	1.52	1.76	2.05	2.27	2.92	N/A
5-Year RP	1.53	1.77	2.06	2.28	2.93	N/A
10-Year RP	1.62	1.86	2.15	2.37	3.02	N/A
20-Year RP	1.71	1.95	2.24	2.46	3.11	N/A
50-Year RP	1.77	2.01	2.30	2.52	3.17	N/A
100-Year RP	1.82	2.06	2.35	2.57	3.22	N/A

Table A- 3: Zone 1, Upper RCP8.5 sea level rise scenario (95% percentile values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.45	-1.11	-0.70	-0.37	N/A	N/A
MWL	-0.26	0.08	0.49	0.82	N/A	N/A
HHWLT	0.94	1.28	1.69	2.02	N/A	N/A
2-Year RP	1.53	1.87	2.28	2.61	N/A	N/A
5-Year RP	1.54	1.88	2.29	2.62	N/A	N/A
10-Year RP	1.63	1.97	2.38	2.71	N/A	N/A
20-Year RP	1.72	2.06	2.47	2.8	N/A	N/A
50-Year RP	1.78	2.12	2.53	2.86	N/A	N/A
100-Year RP	1.83	2.17	2.58	2.91	N/A	N/A

Table A- 4: Zone 1, SSP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.42	-1.13	-0.77	-0.47	N/A	0.16
MWL	-0.23	0.06	0.42	0.72	N/A	1.35
HHWLT	0.97	1.26	1.62	1.92	N/A	2.55
2-Year RP	1.56	1.85	2.21	2.51	N/A	3.14
5-Year RP	1.57	1.86	2.22	2.52	N/A	3.15
10-Year RP	1.66	1.95	2.31	2.61	N/A	3.24
20-Year RP	1.75	2.04	2.4	2.7	N/A	3.33
50-Year RP	1.81	2.1	2.46	2.76	N/A	3.39
100-Year RP	1.86	2.15	2.51	2.81	N/A	3.44

Zone 2: Peggy's Cove, Terrence Bay, Sambro

Table A- 5: Zone 2, RCP4.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.19	-0.97	-0.78	-0.66	N/A	N/A
MWL	-0.18	0.04	0.24	0.36	N/A	N/A
HHWLT	0.78	1.00	1.19	1.31	N/A	N/A
2-Year RP	1.35	1.57	1.76	1.88	N/A	N/A
5-Year RP	1.37	1.59	1.78	1.9	N/A	N/A
10-Year RP	1.46	1.68	1.87	1.99	N/A	N/A
20-Year RP	1.55	1.77	1.96	2.08	N/A	N/A
50-Year RP	1.60	1.82	2.01	2.13	N/A	N/A
100-Year RP	1.65	1.87	2.06	2.18	N/A	N/A

Table A- 6: Zone 2, RCP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.18	-0.93	-0.64	-0.41	0.24	N/A
MWL	-0.17	0.08	0.37	0.60	1.25	N/A
HHWLT	0.79	1.04	1.33	1.56	2.21	N/A
2-Year RP	1.36	1.61	1.90	2.13	2.78	N/A
5-Year RP	1.38	1.63	1.92	2.15	2.80	N/A
10-Year RP	1.47	1.72	2.01	2.24	2.89	N/A
20-Year RP	1.56	1.81	2.10	2.33	2.98	N/A
50-Year RP	1.61	1.86	2.15	2.38	3.03	N/A
100-Year RP	1.66	1.91	2.20	2.43	3.08	N/A

Table A- 7: Zone 2, Upper RCP8.5 sea level rise scenario (95% percentile values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.17	-0.83	-0.41	-0.07	N/A	N/A
MWL	-0.16	0.18	0.60	0.94	N/A	N/A
HHWLT	0.80	1.14	1.56	1.90	N/A	N/A
2-Year RP	1.37	1.71	2.13	2.47	N/A	N/A
5-Year RP	1.39	1.73	2.15	2.49	N/A	N/A
10-Year RP	1.48	1.82	2.24	2.58	N/A	N/A
20-Year RP	1.57	1.91	2.33	2.67	N/A	N/A
50-Year RP	1.62	1.96	2.38	2.72	N/A	N/A
100-Year RP	1.67	2.01	2.43	2.77	N/A	N/A

Table A- 8: Zone 2, SSP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.15	-0.86	-0.50	-0.20	N/A	0.43
MWL	-0.14	0.15	0.51	0.81	N/A	1.44
HHWLT	0.82	1.11	1.47	1.77	N/A	2.40
2-Year RP	1.39	1.68	2.04	2.34	N/A	2.97
5-Year RP	1.41	1.70	2.06	2.36	N/A	2.99
10-Year RP	1.50	1.79	2.15	2.45	N/A	3.08
20-Year RP	1.59	1.88	2.24	2.54	N/A	3.17
50-Year RP	1.64	1.93	2.29	2.59	N/A	3.22
100-Year RP	1.69	1.98	2.34	2.64	N/A	3.27

Zone 3: Halifax, Bedford, Dartmouth, Eastern Passage

Table A- 9: Zone 3, RCP4.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.34	-1.12	-0.92	-0.80	N/A	N/A
MWL	-0.24	-0.02	0.18	0.30	N/A	N/A
HHWLT	0.86	1.08	1.28	1.40	N/A	N/A
2-Year RP	1.20	1.42	1.62	1.74	N/A	N/A
5-Year RP	1.31	1.53	1.73	1.85	N/A	N/A
10-Year RP	1.39	1.61	1.81	1.93	N/A	N/A
20-Year RP	1.48	1.70	1.90	2.02	N/A	N/A
50-Year RP	1.62	1.84	2.04	2.16	N/A	N/A
100-Year RP	1.67	1.89	2.09	2.21	N/A	N/A
200-Year RP	1.75	1.97	2.17	2.29	N/A	N/A
500-Year RP	1.86	2.08	2.28	2.40	N/A	N/A
1000-Year RP	1.94	2.16	2.36	2.48	N/A	N/A

Table A- 10: Zone 3, RCP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.33	-1.08	-0.79	-0.56	0.09	N/A
MWL	-0.23	0.02	0.31	0.54	1.19	N/A
HHWLT	0.87	1.12	1.41	1.64	2.29	N/A
2-Year RP	1.21	1.46	1.75	1.98	2.63	N/A
5-Year RP	1.32	1.57	1.86	2.09	2.74	N/A
10-Year RP	1.40	1.65	1.94	2.17	2.82	N/A
20-Year RP	1.49	1.74	2.03	2.26	2.91	N/A
50-Year RP	1.63	1.88	2.17	2.40	3.05	N/A
100-Year RP	1.68	1.93	2.22	2.45	3.10	N/A
200-Year RP	1.76	2.01	2.30	2.53	3.18	N/A
500-Year RP	1.87	2.12	2.41	2.64	3.29	N/A
1000-Year RP	1.95	2.20	2.49	2.72	3.37	N/A

Table A- 11: Zone 3, Upper RCP8.5 sea level rise scenario (95% percentile values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.32	-0.97	-0.56	-0.22	N/A	N/A
MWL	-0.22	0.13	0.54	0.88	N/A	N/A
HHWLT	0.88	1.23	1.64	1.98	N/A	N/A
2-Year RP	1.22	1.57	1.98	2.32	N/A	N/A
5-Year RP	1.33	1.68	2.09	2.43	N/A	N/A
10-Year RP	1.41	1.76	2.17	2.51	N/A	N/A
20-Year RP	1.50	1.85	2.26	2.60	N/A	N/A
50-Year RP	1.64	1.99	2.40	2.74	N/A	N/A
100-Year RP	1.69	2.04	2.45	2.79	N/A	N/A
200-Year RP	1.77	2.12	2.53	2.87	N/A	N/A
500-Year RP	1.88	2.23	2.64	2.98	N/A	N/A
1000-Year RP	1.96	2.31	2.72	3.06	N/A	N/A

Table A- 12: Zone 3, SSP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.30	-1.01	-0.65	-0.35	N/A	0.28
MWL	-0.20	0.09	0.45	0.75	N/A	1.38
HHWLT	0.90	1.19	1.55	1.85	N/A	2.48
2-Year RP	1.24	1.53	1.89	2.19	N/A	2.82
5-Year RP	1.35	1.64	2.00	2.30	N/A	2.93
10-Year RP	1.43	1.72	2.08	2.38	N/A	3.01
20-Year RP	1.52	1.81	2.17	2.47	N/A	3.10
50-Year RP	1.66	1.95	2.31	2.61	N/A	3.24
100-Year RP	1.71	2.00	2.36	2.66	N/A	3.29
200-Year RP	1.79	2.08	2.44	2.74	N/A	3.37
500-Year RP	1.90	2.19	2.55	2.85	N/A	3.48
1000-Year RP	1.98	2.27	2.63	2.93	N/A	3.56

Zone 4: Lawrencetown, Seaforth, Chezzetcook

Table A- 13: Zone 4, RCP4.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.33	-1.11	-0.91	-0.79	N/A	N/A
MWL	-0.30	-0.08	0.11	0.23	N/A	N/A
HHWLT	0.69	0.90	1.10	1.22	N/A	N/A
2-Year RP	1.16	1.37	1.57	1.69	N/A	N/A
5-Year RP	1.27	1.48	1.68	1.80	N/A	N/A
10-Year RP	1.35	1.56	1.76	1.88	N/A	N/A
20-Year RP	1.45	1.66	1.86	1.98	N/A	N/A
50-Year RP	1.50	1.71	1.91	2.03	N/A	N/A
100-Year RP	1.54	1.75	1.95	2.07	N/A	N/A

Table A- 14: Zone 4, RCP8.5 sea level rise scenario (median values). Water levels are in CGVD2013

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.31	-1.07	-0.78	-0.55	0.10	N/A
MWL	-0.29	-0.04	0.25	0.47	1.12	N/A
HHWLT	0.70	0.94	1.23	1.46	2.11	N/A
2-Year RP	1.17	1.41	1.70	1.93	2.58	N/A
5-Year RP	1.28	1.52	1.81	2.04	2.69	N/A
10-Year RP	1.36	1.60	1.89	2.12	2.77	N/A
20-Year RP	1.46	1.70	1.99	2.22	2.87	N/A
50-Year RP	1.51	1.75	2.04	2.27	2.92	N/A
100-Year RP	1.55	1.79	2.08	2.31	2.96	N/A

Table A- 15: Zone 4, Upper RCP8.5 sea level rise scenario (95% percentile values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.30	-0.97	-0.55	-0.21	N/A	N/A
MWL	-0.27	0.06	0.48	0.81	N/A	N/A
HHWLT	0.72	1.05	1.47	1.80	N/A	N/A
2-Year RP	1.19	1.52	1.94	2.27	N/A	N/A
5-Year RP	1.30	1.63	2.05	2.38	N/A	N/A
10-Year RP	1.38	1.71	2.13	2.46	N/A	N/A
20-Year RP	1.48	1.81	2.23	2.56	N/A	N/A
50-Year RP	1.53	1.86	2.28	2.61	N/A	N/A
100-Year RP	1.57	1.90	2.32	2.65	N/A	N/A

Table A- 16: Zone 4, SSP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.29	-1.00	-0.64	-0.34	N/A	0.29
MWL	-0.26	0.03	0.39	0.69	N/A	1.32
HHWLT	0.73	1.02	1.38	1.68	N/A	2.31
2-Year RP	1.20	1.49	1.85	2.15	N/A	2.78
5-Year RP	1.31	1.60	1.96	2.26	N/A	2.89
10-Year RP	1.39	1.68	2.04	2.34	N/A	2.97
20-Year RP	1.49	1.78	2.14	2.44	N/A	3.07
50-Year RP	1.54	1.83	2.19	2.49	N/A	3.12
100-Year RP	1.58	1.87	2.23	2.53	N/A	3.16

Zone 5: Clam Harbour, Tangier, Sheet Harbour

Table A- 17: Zone 5, RCP4.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.36	-1.16	-0.97	-0.85	N/A	N/A
MWL	-0.33	-0.12	0.07	0.18	N/A	N/A
HHWLT	0.65	0.86	1.05	1.16	N/A	N/A
2-Year RP	1.12	1.33	1.52	1.63	N/A	N/A
5-Year RP	1.22	1.43	1.62	1.73	N/A	N/A
10-Year RP	1.32	1.53	1.72	1.83	N/A	N/A
20-Year RP	1.41	1.62	1.81	1.92	N/A	N/A
50-Year RP	1.45	1.66	1.85	1.96	N/A	N/A
100-Year RP	1.49	1.70	1.89	2.00	N/A	N/A

Table A- 18: Zone 5, RCP8.5 sea level rise scenario (median Values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.35	-1.12	-0.83	-0.62	0.03	N/A
MWL	-0.32	-0.09	0.20	0.41	1.06	N/A
HHWLT	0.66	0.90	1.18	1.39	2.04	N/A
2-Year RP	1.13	1.37	1.65	1.86	2.51	N/A
5-Year RP	1.23	1.47	1.75	1.96	2.61	N/A
10-Year RP	1.33	1.57	1.85	2.06	2.71	N/A
20-Year RP	1.42	1.66	1.94	2.15	2.80	N/A
50-Year RP	1.46	1.70	1.98	2.19	2.84	N/A
100-Year RP	1.50	1.74	2.02	2.23	2.88	N/A

Table A- 19: Zone 5, Upper RCP8.5 sea level rise scenario (95% percentile values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.33	-1.01	-0.61	-0.29	N/A	N/A
MWL	-0.30	0.02	0.42	0.74	N/A	N/A
HHWLT	0.68	1.00	1.40	1.73	N/A	N/A
2-Year RP	1.15	1.47	1.87	2.20	N/A	N/A
5-Year RP	1.25	1.57	1.97	2.30	N/A	N/A
10-Year RP	1.35	1.67	2.07	2.40	N/A	N/A
20-Year RP	1.44	1.76	2.16	2.49	N/A	N/A
50-Year RP	1.48	1.80	2.20	2.53	N/A	N/A
100-Year RP	1.52	1.84	2.24	2.57	N/A	N/A

Table A- 20: Zone 5, SSP8.5 sea level rise scenario (median values). Water levels are in CGVD2013.

Water Level (m CGVD2013)	2020	2050	2080	2100	2100 + AIS	2150
LLWLT	-1.32	-1.04	-0.67	-0.38	N/A	0.26
MWL	-0.29	0.00	0.36	0.66	N/A	1.29
HHWLT	0.69	0.98	1.34	1.64	N/A	2.27
2-Year RP	1.16	1.45	1.81	2.11	N/A	2.74
5-Year RP	1.26	1.55	1.91	2.21	N/A	2.84
10-Year RP	1.36	1.65	2.01	2.31	N/A	2.94
20-Year RP	1.45	1.74	2.10	2.40	N/A	3.03
50-Year RP	1.49	1.78	2.14	2.44	N/A	3.07
100-Year RP	1.53	1.82	2.18	2.48	N/A	3.11

APPENDIX B

Extreme Value Analysis for Water Levels

The extreme water levels due to tides and surge (excluding SLR) for Zone 3 were calculated using a statistical methodology known as extreme value analysis. This methodology could only be applied for Zone 3 since this is the only zone with long-term tide gauge data available. Extreme value analysis is typically used to estimate the probability of events (i.e., the RP of storm events) based on observed data, usually collected over a relatively long period of time to be statistically representative for the extreme analysis. The analysis was done using the total water level peaks measured by the BIO tide gauge after detrending for historical SLR. The results of the extreme value analysis are shown in Figure A- 2. This plot includes the water levels of the highest storm events recorded on the BIO tide gauge and the calculated extreme water levels for the corresponding RP using the extreme value analysis. Note the x-axis has a logarithmic distribution, and therefore the increase in water levels for longer return periods is not linear.

It is important to note that there is uncertainty associated with the estimation of extreme water levels, especially for RPs much larger than the duration of the observations (for example, 200 to 1000 years). In simple terms, the longer the return period, the larger the uncertainty. The tide gauge data used to calculate extreme water levels for Zone 3 has a duration of approximately 100 years. The calculated extreme water levels with RPs greater than 100 years are much more sensitive to the extreme value fit calculated from the available tide gauge data, which leads to greater uncertainty in derived values.

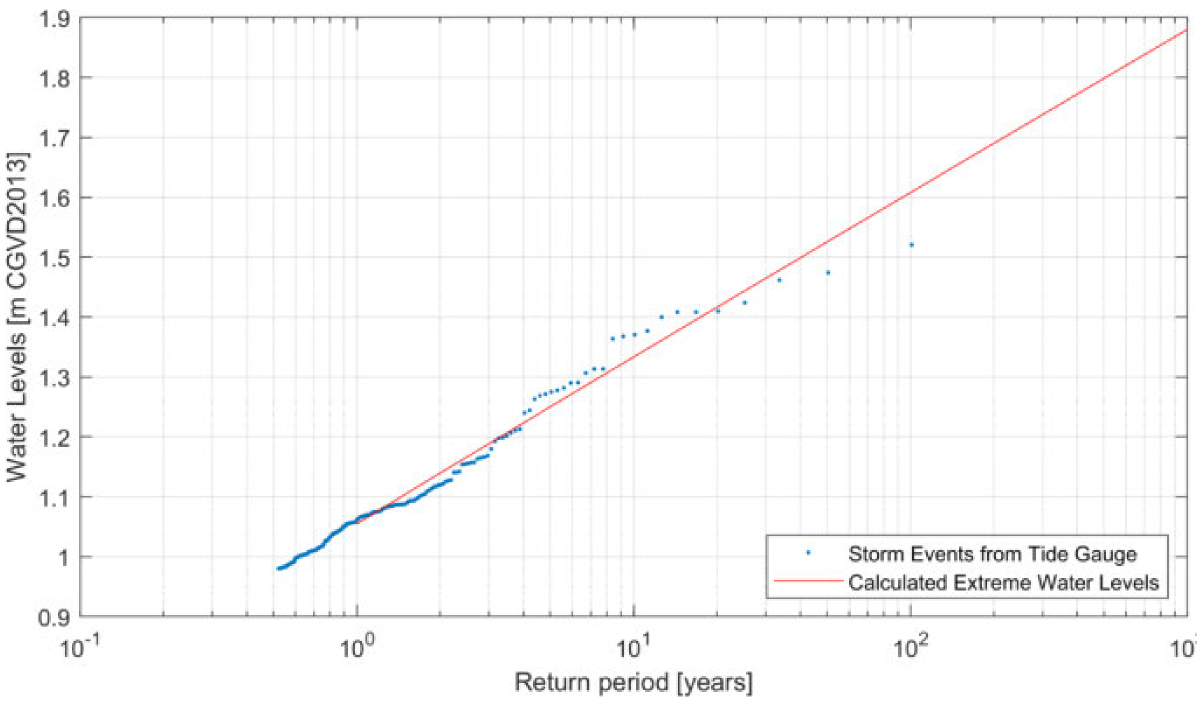

Figure A- 2: Results of the extreme value analysis. This includes the recorded peaks of storm events from the BIO tide gauge and the calculated extreme water levels to the corresponding RP. Note the x-axis has a logarithmic distribution, and therefore the increase in water levels for longer return periods is not linear.

APPENDIX C

Sea Level Rise Projections

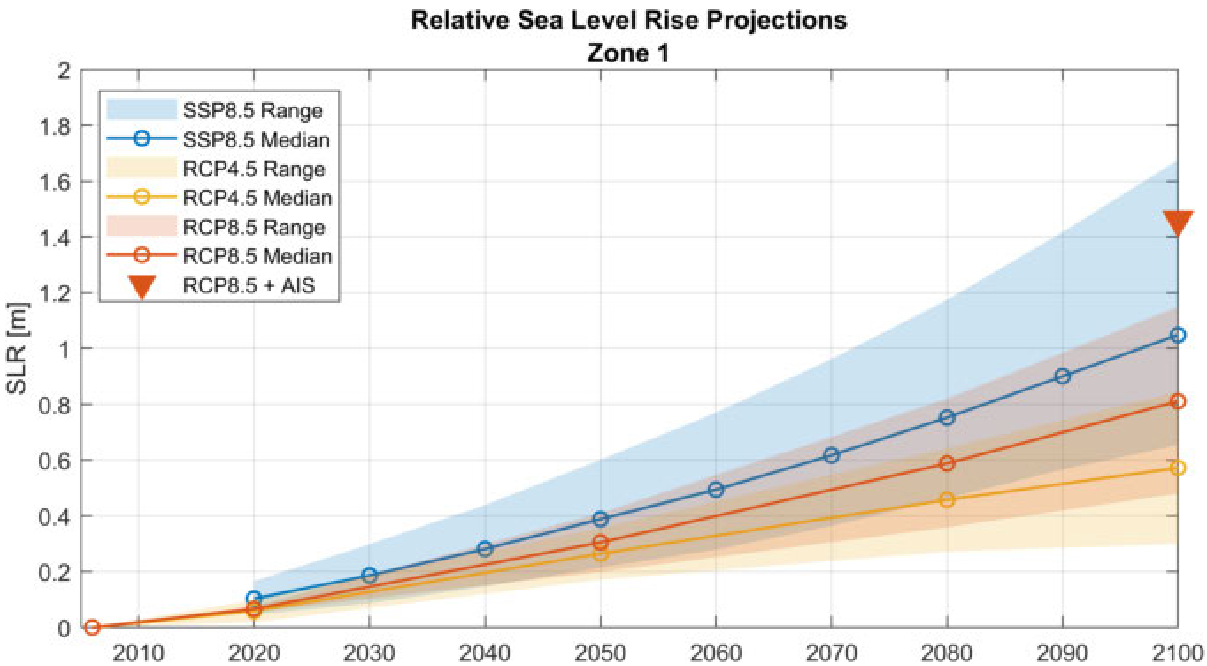

Figure A- 3: Sea level rise projections for Zone 1 for the various scenarios. The 5th and 95th percentiles are the shaded lower and upper limits, while the solid line is the median projection.

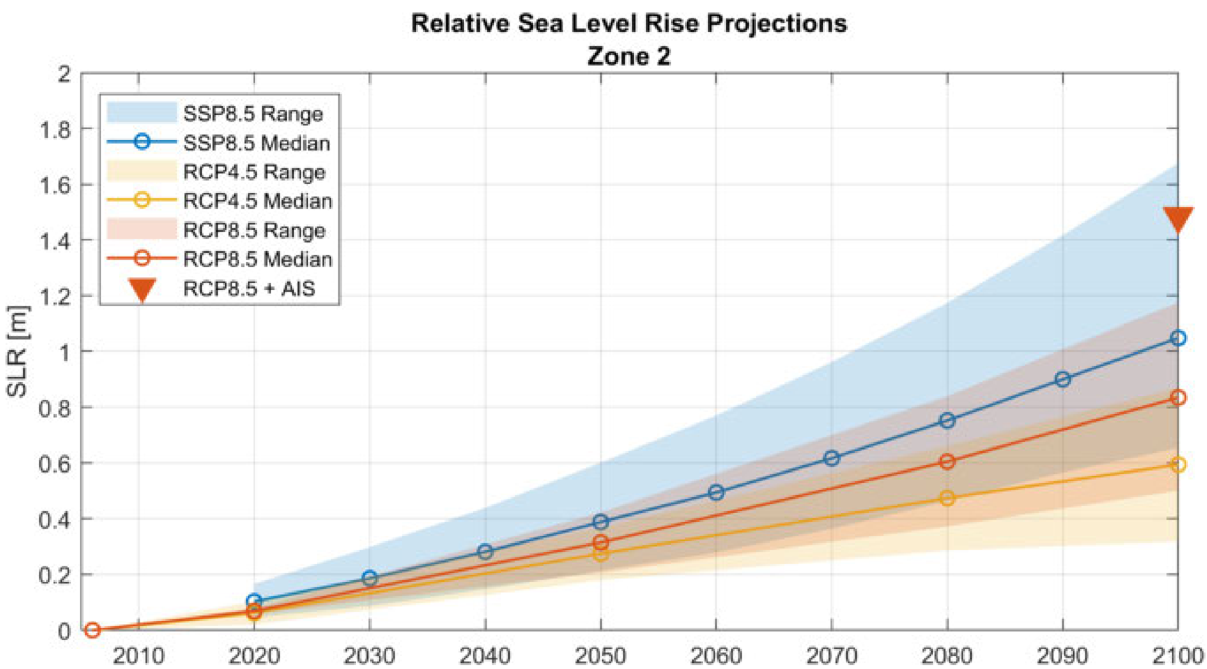

Figure A- 4: Sea level rise projections for Zone 2 for the various scenarios. The 5th and 95th percentiles are the shaded lower and upper limits, while the solid line is the median projection.

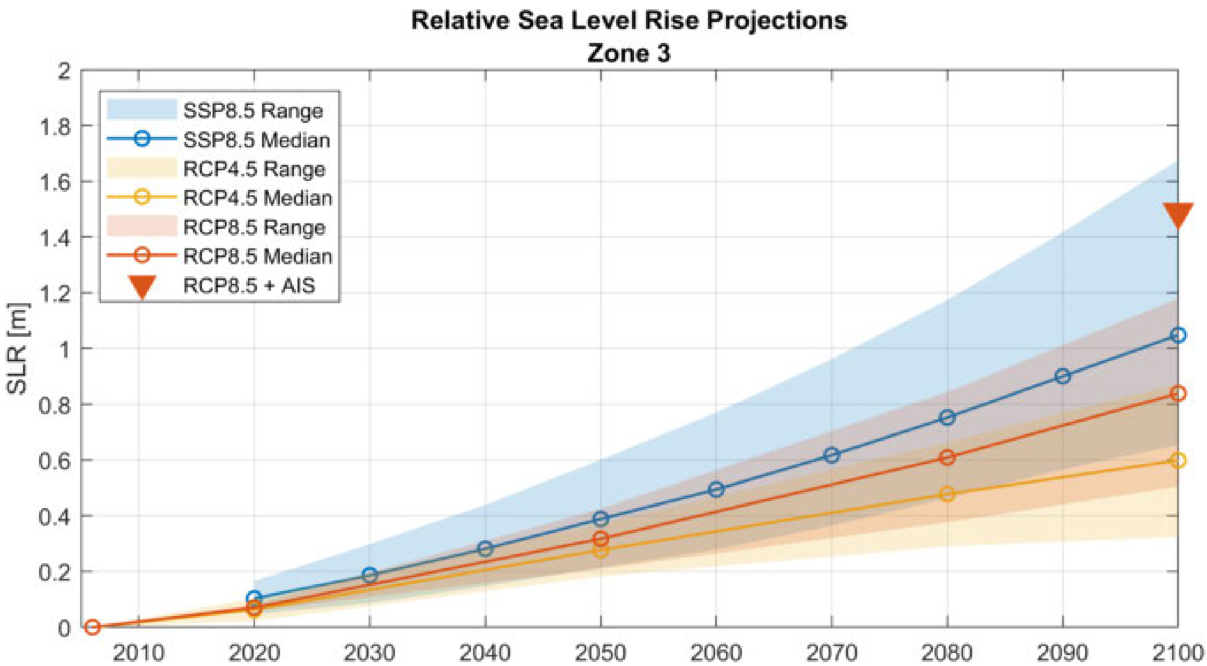

Figure A- 5: Sea level rise projections for Zone 3 for the various scenarios. The 5th and 95th percentiles are the shaded lower and upper limits, while the solid line is the median projection.

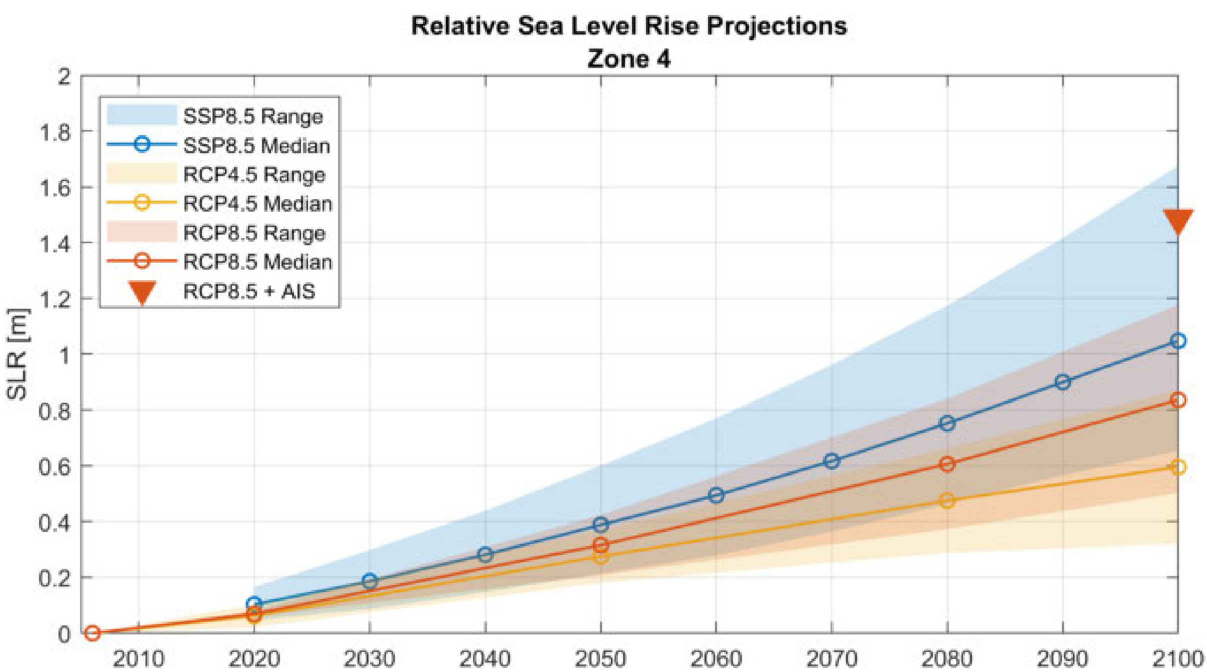

Figure A- 6: Sea level rise projections for Zone 4 for the various scenarios. The 5th and 95th percentiles are the shaded lower and upper limits, while the solid line is the median projection.

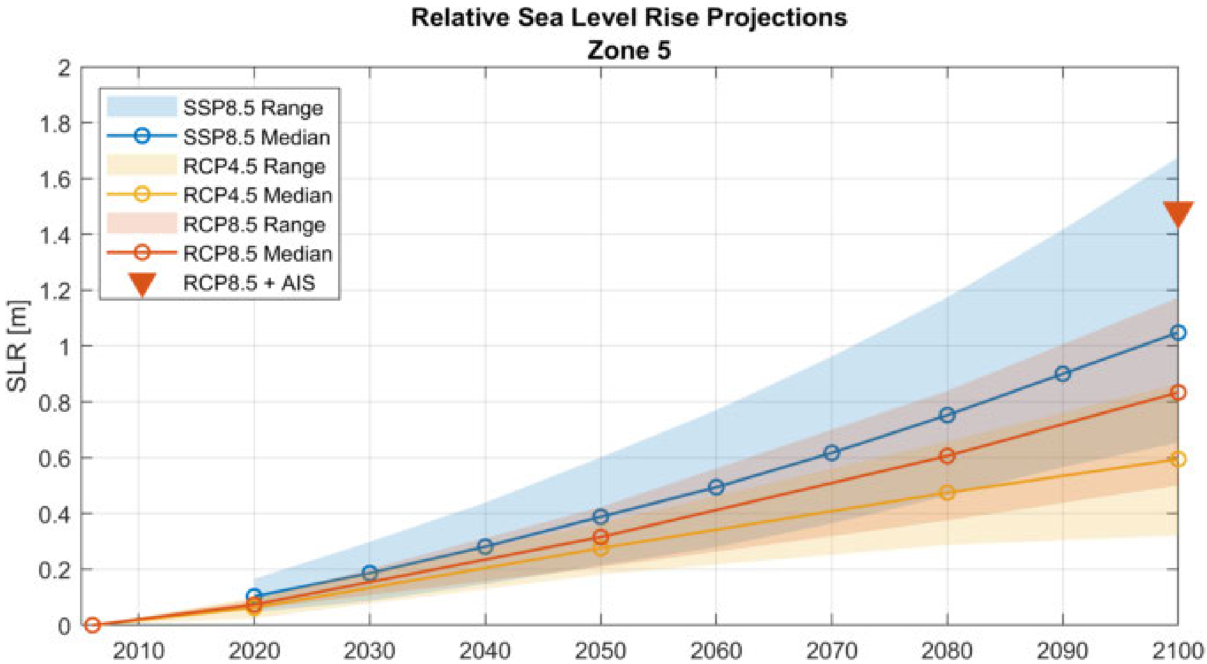

Figure A- 7: Sea level rise projections for Zone 5 for the various scenarios. The 5th and 95th percentiles are the shaded lower and upper limits, while the solid line is the median projection.

APPENDIX D

Tidal Elevations & Sea Level Rise

The tidal elevations provided by CHS and CAN-EWLAT described in Chapter 3 are adjusted to a common epoch of 2010 (Robin *et al.*, 2016). This correction is performed because several series of water level measurements used to calculate tidal elevations at each port are from previous years, and water levels have fluctuated with time due to sea level rise. For example, a mean water level that is based on measurements from 1990 would underestimate current mean water levels due to the SLR that has occurred since then. Further details on this methodology are available in the paper developed by Robin *et al.* (2016). The equation for the correction of the water level to bring it to a common epoch of 2010 is:

$$Epoch_{2010} = Epoch_{Obs} + SLR_{Adjust}$$

When analyzing tide gauge data at the BIO, it was found that in recent years the frequency of the water levels exceeding the HHWLT for Halifax has increased, as shown in Figure A- 8. This could be due to the HHWLT being set to an epoch of 2010. In order to be conservative, the SLR values for 2020 from the various sources (NRCAN and NASA) were added to the tidal elevations. The justification for this was based on the tidal elevations being set to an epoch of 2010, which would underestimate tidal elevations provided for 2020 in this report. Sea level rise projections are based on a baseline year of 2006. This could result in the tidal elevations being slightly greater due to sea level rise from 2006 to 2010 being added to the tidal elevations, however, it was a deemed a more appropriate approach to provide conservative tidal elevations, rather than leaving them set to an epoch of 2010. This decision was further supported by the analysis of the tide gauge data, demonstrating a significant increase in frequency of water levels exceeding HHWLT (Figure A- 8).

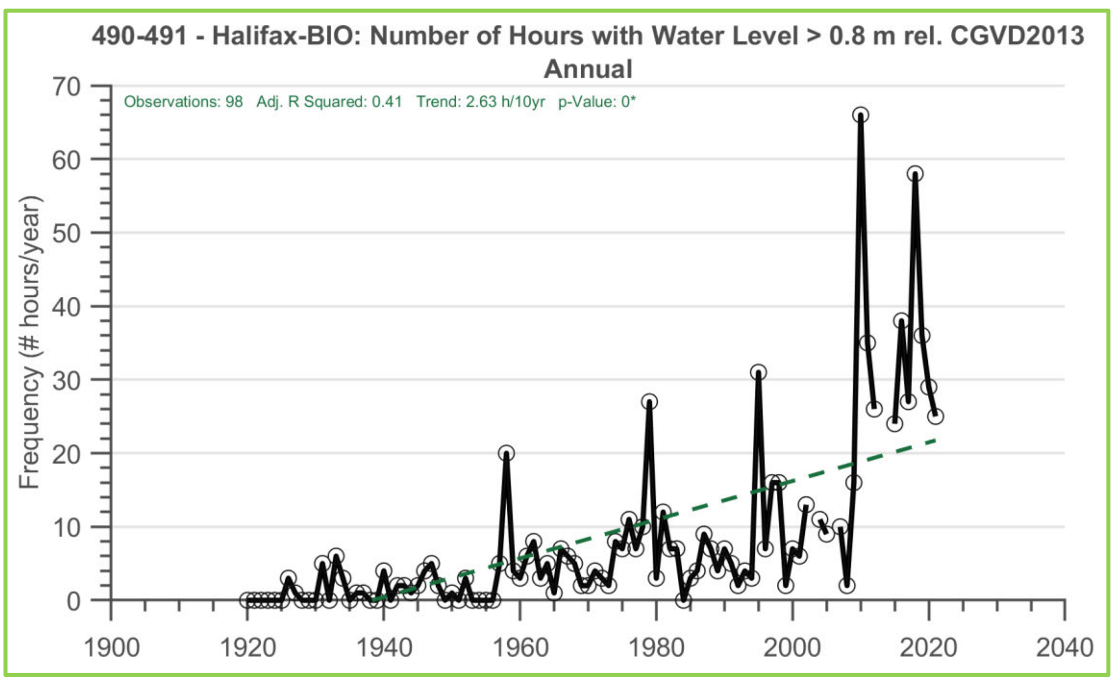

Figure A- 8: Frequency of tide gauge data at the BIO station exceeding the HHWLT for Halifax from CHS.

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