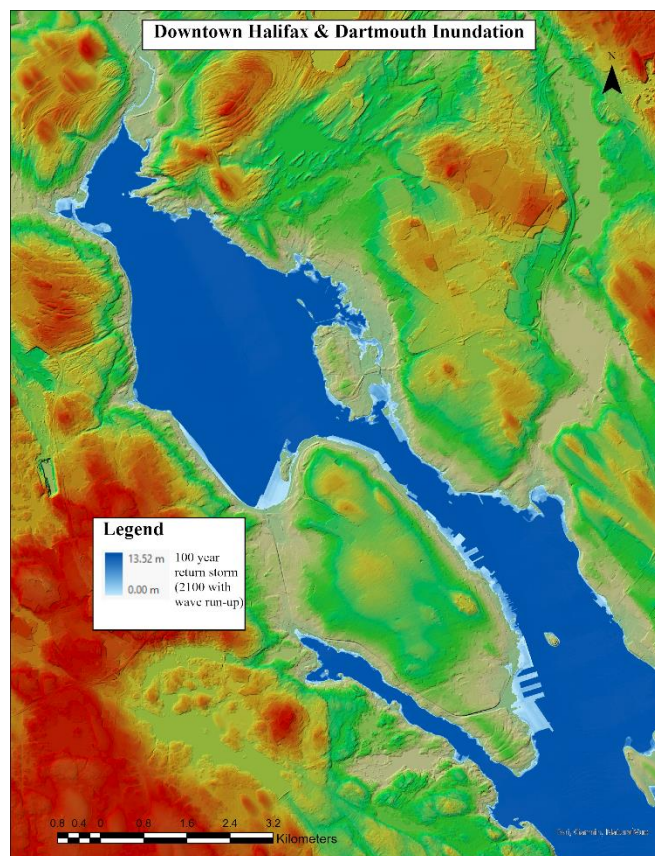


---

# CLIMATLANTIC STORM SURGE FLOOD LAYERS TODAY AND IN THE FUTURE

---

Methods to Construct Flood Layers for Atlantic Canada



## How to cite this work and report:

NSCC Applied Geomatics Research Group. 2024. CLIMAtlantic Storm Surge Flood Layers Today and in the Future: Methods to Construct Flood Layers for Atlantic Canada. Technical Report delivered to CLIMAtlantic, Applied Geomatics Research Group, NSCC Middleton, NS.

## Copyright and Acknowledgement

The Applied Geomatics Research Group of the Nova Scotia Community College maintains full ownership of all data collected by equipment owned by NSCC and agrees to provide the end user who commissions the data collection a license to use the data for the purpose they were collected for upon written consent by AGRG-NSCC. The end user may make unlimited copies of the data for internal use; derive products from the data, release graphics and hardcopy with the copyright acknowledgement of **“Data acquired and processed by the Applied Geomatics Research Group, NSCC”**. Data acquired using this technology and the intellectual property (IP) associated with processing these data are owned by AGRG/NSCC and data will not be shared without permission of AGRG/NSCC.

## EXECUTIVE SUMMARY

AGRГ constructed flood layers encompassing Atlantic Canada, including Les Îles-de-la-Madeleine, and a Hurricane Fiona high water wrack line for CLIMAtlantic. A total of 16 flood scenarios were considered under the scope of this project, including floods resulting from 20-year and 100-year storm surge considered with current day conditions and with relative sea-level (RSL) rise conditions for 2050, 2100, and 2150. Each variation was also constructed with and without a 0.5 m and 1.0 m wave run-up for layers constructed with 20-year and 100-year storm surge, respectively. A series of geographic data were acquired from a variety of sources to build flood products covering Atlantic Canada. Storm Surge projections from Zhang & Sheng (2013), Higher High Water Large Tide (HHWLT) points from the Canadian Hydrographic Service (2015), RSL rise grids from the IPCC AR6 report (James & Brierley-Green, in prep), and DEM data (Natural Resources Canada, 2023-2024) (Solomon, 2024) were used to synthesize vector flood layers and raster flood depth layers. The DEM data were hydrologically enforced using Python programming to simulate real-world hydrological behavior during flood events. Real time kinematic GNSS observations (Jardine Consulting, 2023) (Bérubé, 2023) of debris and wrack lines were acquired post-hurricane Fiona and used to develop the high-water wrack line. Data products were constructed using several innovative GIS analysis techniques and Python scripts.

## CONTENTS

Executive Summary .....	2
List of Figures .....	3
List of Tables .....	4
1 Introduction .....	5
2 Methods.....	9
2.0 Data Inputs .....	9
2.1 Data Pre-processing.....	17
Hydro Enforcement Methods .....	20
3 Flood Products Generation.....	21
Vector flood layer generation.....	21
Flood Depth Raster generation .....	23
4 Concluding Remarks .....	26
5 References .....	28

## LIST OF FIGURES

Figure 1 This map displays the high resolution lidar coverage in red over Atlantic Canada. ....	7
Figure 2 This map highlights the Hurricane Fiona Wrack-Line elevation raw data acquired by AGRG, Bérubé D (2023), and Jardine Consulting (2023). ....	8
Figure 3 The Zhang & Sheng (2013) 100-year return storm surge grid. ....	12
Figure 4 The medium confidence (83%) AR6 SSP5-8.5 RSL grid for 2100 provided by James & Brierley-Green (in prep) relative to CGVD 2013. ....	14
Figure 5 The HHWLT raster grid file processed from the Canadian Hydrographic Service (2015) HyVSEP point data. ....	15
Figure 6 The processing zones used in this project. Lidar DEM coverage in Nova Scotia, New Brunswick, and Newfoundland was divided into smaller scale chunks for processing. ....	18
Figure 7 This illustration describes the watershed methodology whereby pixels belonging to each watershed were assigned the value of the nearest pour point.....	19
Figure 8 This graphic illustrates the process used to hydrologically condition the DEM. Panel A shows an inundated stream that stops at a roadway present in the DEM because there is no hydro-enforcement line. Panel B shows that water in the stream will flow under the road within the DEM when the hydro-enforcement line is present. ....	20
Figure 9 The above graphic depicts the method used to generate the flood layers in this project. ....	21
Figure 10 The 100yr return storm event flood layers for year 2100 centered on Sydney, Nova Scotia. The top map frame displays the ‘without wave run-up’ variant and the bottom map frame displays the ‘with wave run-up’ (+ 1.0 m) variant. ....	22

Figure 11 The 100yr return storm event raster flood depth layers for year 2100 centered on Sydney, Nova Scotia. The top map frame displays the ‘without wave run-up’ variant whilst the bottom map frame displays the ‘with wave run-up’ (+ 1.0 m) variant. ....24

Figure 12 This depiction, centered on Sydney, Nova Scotia, displays flood layers produced using 20-year return storm surge grids (A) compared with flood layers produced using 100-year return storm surge grids (B). Flood layers in (A) have an additional 0.5 m wave run-up value incorporated and flood layers in (B) have an extra 1.0 m wave run-up value added. ....25

Figure 13 This figure outlines the workflow used to derive a Hurricane Fiona wrack line from raw data observations. Panel (A) illustrates that elevation values stored in raw data measurements (red points) were appended to points (yellow points) generated along the coastline (red line) that were within a 1km buffer area (black circle). Panel (B) describes the interpolation algorithm used to derive elevation values at unknown points (blue) that fell outside of the 1km buffer around known points (red). Panel (C) highlights the raster layer that was created when the interpolated point file was converted to a raster geo-tiff. Panel (D) displays the final wrack line file that was created from the polygon product derived from the conditional raster calculation executed to select DEM pixels below the elevation of the wrack line raster layer. Please be advised that the illustrations shown above are not to drawn to scale and are only intended to aid with the understanding of the project methods. ....26

## LIST OF TABLES

Table 1 The 20-year total return water levels at 2100 m (CGVD2013) including 0.5 m wave run-up. The zone numbers are from R J Daigle Enviro 2020 as used in the NB Flood Hazard Maps. ....10

Table 2 The 100-year total return water Levels at 2100 m (CGVD2013) including 1 m wave run-up. Zone numbers are from R J Daigle Enviro 2020 as used in NB Flood Hazard Maps. ....11

Table 3 Selected locations within Atlantic Canada were used to compare upper confidence (95%) AR5 RCP 8.5 RSL projections with medium confidence (83%) AR6 SSP5-8.5 RSL projections. Medium confidence (83%) AR6 SSP5-8.5 RSL projection data tends to agree with upper confidence (95%) AR5 RCP 8.5 RSL data in the year 2050 with an average difference of –1.1 cm. Medium confidence (83%) AR6 SSP5-8.5 RSL projection data tends to deviate further above upper confidence (95%) AR5 RCP 8.5 RSL predictions in 2100 and 2150, with an average difference of 13.7 cm and 35.5 cm, respectively. ....13

## 1 INTRODUCTION

The ever-ensuing threat of climate change has and continues to cause global sea levels to rise. This global trend will cause an increase in flooding on an international scale. The Atlantic Canadian region is expected to undergo significant RSL rise over the next century. Relative sea-level rise compounded with the expected increase in the severity of hurricanes in the Atlantic over the coming decades poses a significant flood risk to coastal communities in Atlantic Canada (Environmental Defense Fund, 2024). Now more than ever Atlantic Canadians need access to accurate coastal flooding predictions that will enable them to prepare for and mitigate the damages resulting from future coastal flooding events.

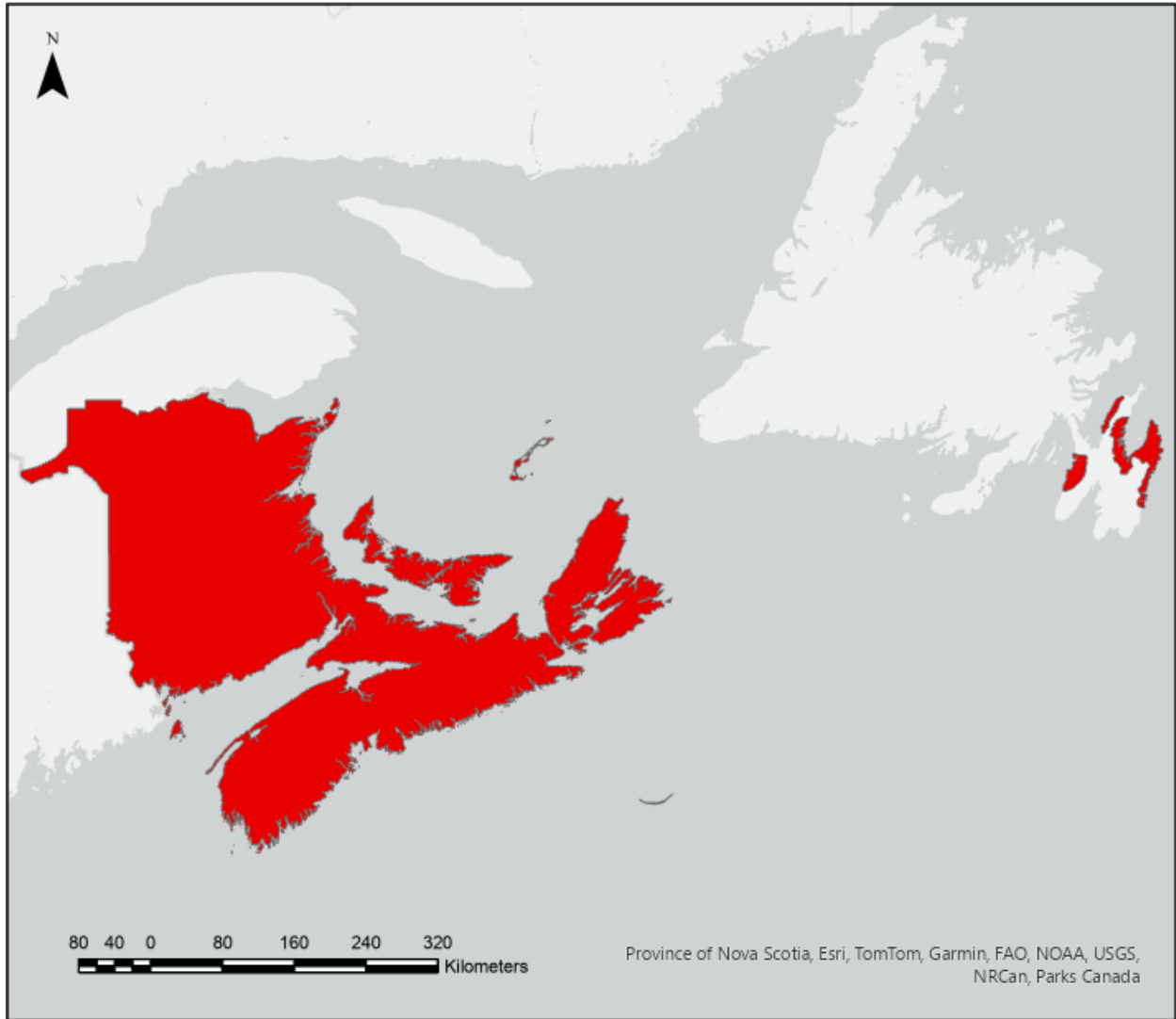
CLIMAtlantic engaged AGRG with a contract to develop vector flood layers and raster flood depth layers covering Atlantic Canada, including Les Îles-de-la-Madeleine, that forecast inundation resulting from future severe storm events. The vector and raster flood layers represent current day and future inundation predictions resulting from 20-year and 100-year return storm events. Storm surge grids developed by Zhang & Sheng (2013) were used as storm surge input data. The storm surge grids (Zhang & Sheng, 2013) were considered underestimates of the true potential height of storm surge in Atlantic Canada. AGRG accounted for underestimates of Zhang & Sheng (2013) by treating the 50-year return storm surge grid as a 20-year return storm surge grid and adding a 0.5 m and 1.0 m wave run-up value to 50-year return and 100-year return storm surge grids, respectively. The years 2020, 2050, 2100, and 2150 were considered with and without 0.5 m and 1.0 m wave run-up values for 20-year and 100-year return storm events. Relative sea-level (RSL) rise projection grids from James & Brierley-Green (in prep) based on the IPCC AR6 report were used to build flood layers predicting inundation for the future years. The RSL grids from James & Brierley-Green (in prep) were produced considering global sea-level rise trends together with isostatic adjustment. All flood conditions were considered with Higher High Water Large Tide (HHWLT), a grid file derived from HyVSEP points provided by the Canadian Hydrographic Service (CHS, 2015) and described by Robin *et al* (2015). High Resolution Digital Elevation Models (DEMs) provided by Natural Resources Canada (NRCAN, 2024) and Jasmine Solomon (Solomon, 2024), covering parts of New Brunswick, Prince Edward Island (PEI), Les Îles-de-la-Madeleine and portions of Newfoundland and Labrador (NFLD), together with DEMs produced at AGRG covering Nova Scotia and parts of New Brunswick were used as an elevation surface to construct the flood layers. Elevation data provided by NRCAN in the Canadian Digital Elevation Model (2023) was used as an elevation surface for most of Newfoundland and all of Labrador where high resolution lidar DEM data were unavailable. Total lidar coverage of Atlantic Canada is shown in (Figure 1).

HHWLT, RSL, and storm surge grids were resampled to match the resolution of the underlying elevation data, producing intermediate HHWLT, RSL, and storm surge layers. The intermediate HHWLT, RSL, and storm surge layers were added together, forming flood level raster layers. Pixels in the underlying DEMs with an elevation less than that of the overlying

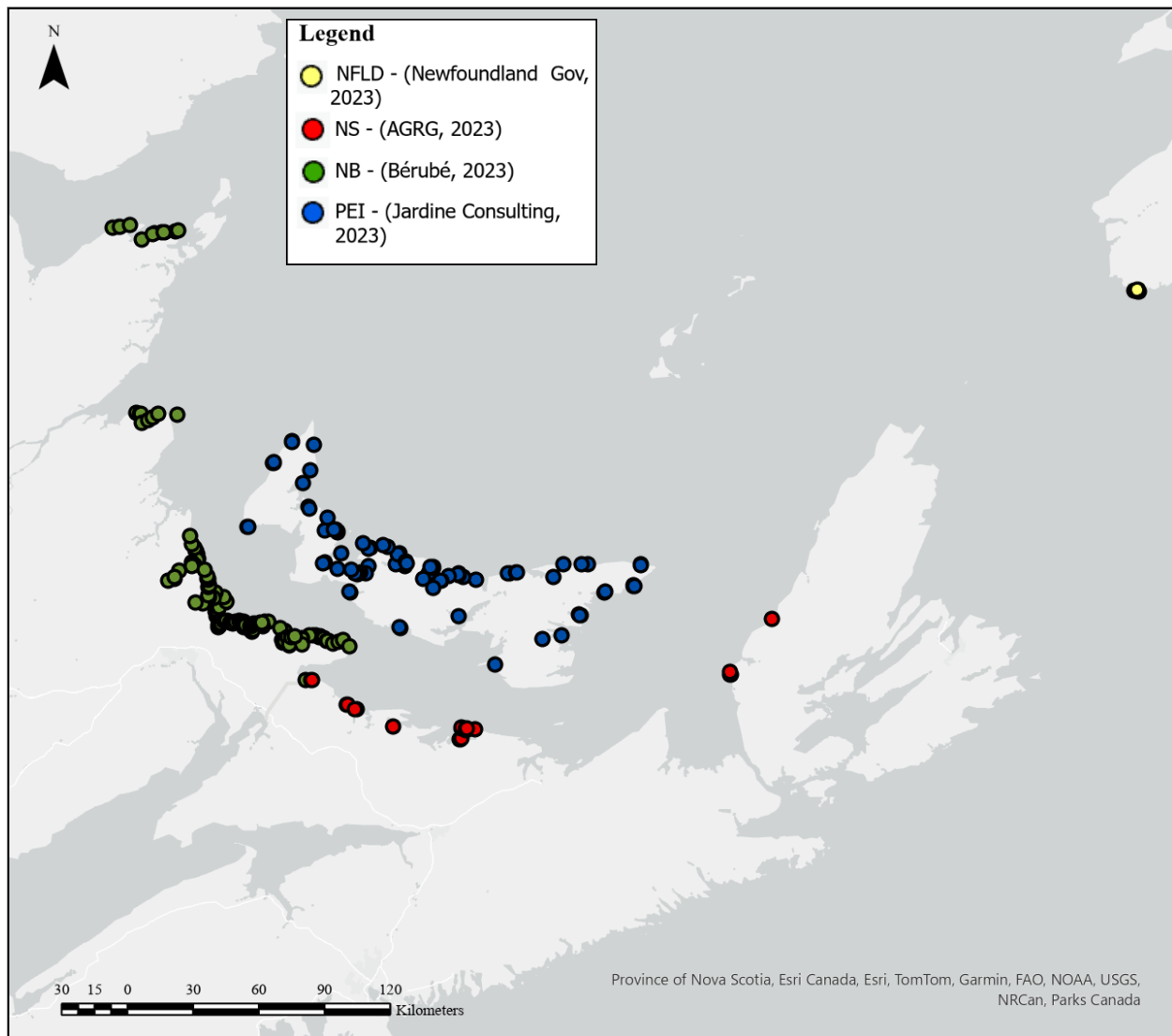
flood level raster layers were considered inundated. These pixels were extracted from the DEM using a combination of methods in ArcGIS Pro and Python.

AGRGR was also tasked with developing Hurricane Fiona high water lines encompassing the extent of available data. Hurricane Fiona high-water lines were derived using GPS referenced elevation data acquired by researchers and agencies in New Brunswick and PEI (Bérubé & Jardine Consulting, 2023), as well as the research staff at AGRGR who compiled wrack line elevation data for Nova Scotia (Figure 2). The Government of NFLD used oblique ortho photos imaging portions of NFLD to derive high-water lines for the area. Hurricane Fiona high-water lines covering PEI, Nova Scotia, and New Brunswick were interpolated from the points over the extent of available data using processing techniques in ArcGIS Pro and Python.

CLIMAtlantic received vector flood and raster flood depth layers that cover the extent of Atlantic Canada for each of 16 agreed upon flooding scenarios, plus a vectorized Hurricane Fiona high-water line. CLIMAtlantic also received all hydrologically enforced digital elevation models (DEMs) used to build the flood layers.



**Figure 1** This map displays the high resolution lidar coverage in red over Atlantic Canada.



**Figure 2** This map highlights the Hurricane Fiona Wrack-Line elevation raw data acquired by AGRG, Bérubé D (2023), and Jardine Consulting (2023).

## 2 METHODS

### 2.0 DATA INPUTS

Storm surge return period water level data were provided by Zhang & Sheng (2013). Their study produced storm surge water level return periods using a parametric vortex simulation to estimate surge conditions for 50-year and 100-year return storm surge across the Atlantic Ocean (Figure 3). The simulation produced was based on water levels derived from atmospheric variables including wind & pressure in a six-hour time step, thus, producing surge levels at 6-hour intervals (Zhang & Sheng, 2013). The relatively short-lived nature of hurricane induced storm surge makes it unlikely that measurements obtained at 6-hour intervals captured the maximum water level reached by the storm surge reported by Zhang & Sheng (2013). AGRG believed the 50-year and 100-year storm surge grids by Zhang & Sheng (2013) underestimated the true potential storm surge height resulting from 50-year and 100-year storms in Atlantic Canada. CLIMAtlantic undertook a preliminary comparison between flood levels produced using Zhang & Shang (2013) storm surge and flood layers produced by R J Daigle Enviro (2020) for the NB Flood Hazard Maps, which incorporated storm surge model results from Bernier (2005). Storm surge model results from Bernier (2005) are believed to underestimate the true potential storm surge in Atlantic Canada (Webster *et al*, 2012), although their model results were the only data available and necessitated their use for building NB flood layers. CLIMAtlantic found flood layers produced by R J Daigle for 20-year return water levels projected to 2100 agreed closely with flood levels produced for 2100 using Zhang & Sheng (2013) 50-year return storm surge with a 0.5 m wave run-up added (Table 1). CLIMAtlantic also determined that flood layers produced by R J Daigle for 100-year return water levels projected to 2100 agreed closely with flood levels produced for 2100 using Zhang & Sheng (2013) 100-year return storm surge with a 1.0 m wave run-up added (Table 2). The methods used in this project treat the 50-year return storm surge grid as a 20-year return storm surge grid to compensate for potential underestimates of Zhang & Sheng (2013). AGRG also added wave run-up values of 0.5 m and 1.0 m to the 50-year and 100-year storm surge grids, respectively.

**Table 1** The 20-year total return water levels at 2100 m (CGVD2013) including 0.5 m wave run-up. The zone numbers are from R J Daigle Enviro 2020 as used in the NB Flood Hazard Maps.

<b>Zone</b>	<b>CLIMAtlantic (proposed) Zhang &amp; Sheng (2013)</b>	<b>CLIMAtlantic (proposed + 0.5 m wave run-up)</b>	<b>NB Flood Hazard Map</b>	<b>Difference</b>
1	3.2	3.7	3.7	0.0
2	2.8	3.3	3.3	0.0
3	2.4	2.9	3.1	-0.2
4	2.3	2.8	2.8	0.0
5	1.9	2.4	2.5	-0.1
6	2.3	2.8	3.0	-0.2
7	2.3	2.8	3.1	-0.3
8	2.4	2.9	3.3	-0.4
9	2.3	2.8	3.1	-0.3
10	2.9	3.4	3.2	+0.2
11	5.1	5.6	5.9	-0.3
12	5.5	6.0	6.0	0.0
13	7.9	8.4	8.5	-0.1
14	9.7	10.2	9.5	+0.7

**Table 2** The 100-year total return water Levels at 2100 m (CGVD2013) including 1 m wave run-up. Zone numbers are from R J Daigle Enviro 2020 as used in NB Flood Hazard Maps.

<b>Zone</b>	<b>CLIMAtlantic (proposed) Zhang &amp; Sheng (2013) + 1.0 m wave run-up</b>	<b>NB Flood Hazard Map</b>	<b>Difference</b>
1	4.3	4.2	+0.1
2	3.8	3.7	+0.1
3	3.5	3.4	+0.1
4	3.4	3.1	+0.3
5	3.0	2.7	+0.3
6	3.4	3.4	0.0
7	3.4	3.5	-0.1
8	3.5	3.7	-0.2
9	3.4	3.5	-0.1
10	4.0	4.2	-0.2
11	6.1	6.1	0.0
12	6.5	6.2	+0.3
13	8.6	8.7	-0.1
14	9.9	9.7	+0.2

Storm surge grids were provided as raster geo-tiffs with a pixel resolution of  $0.0667 \times 0.0667$  degrees ( $6248.4 \times 6248.4$  m) (Figure 3). The grid files were provided in WGS 1984 and projected to the custom Mercator Atlantic Canada projection (Appendix 1).

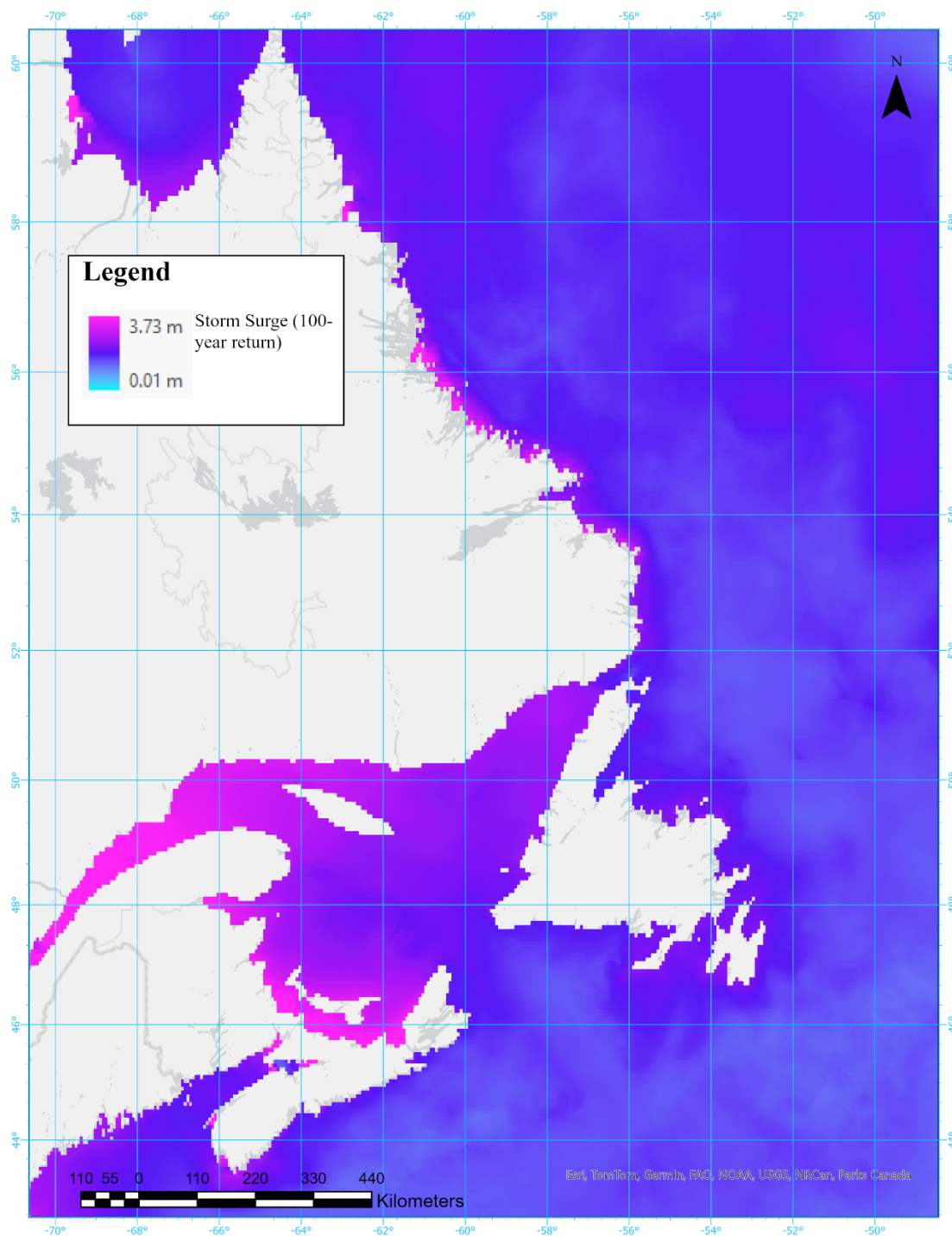


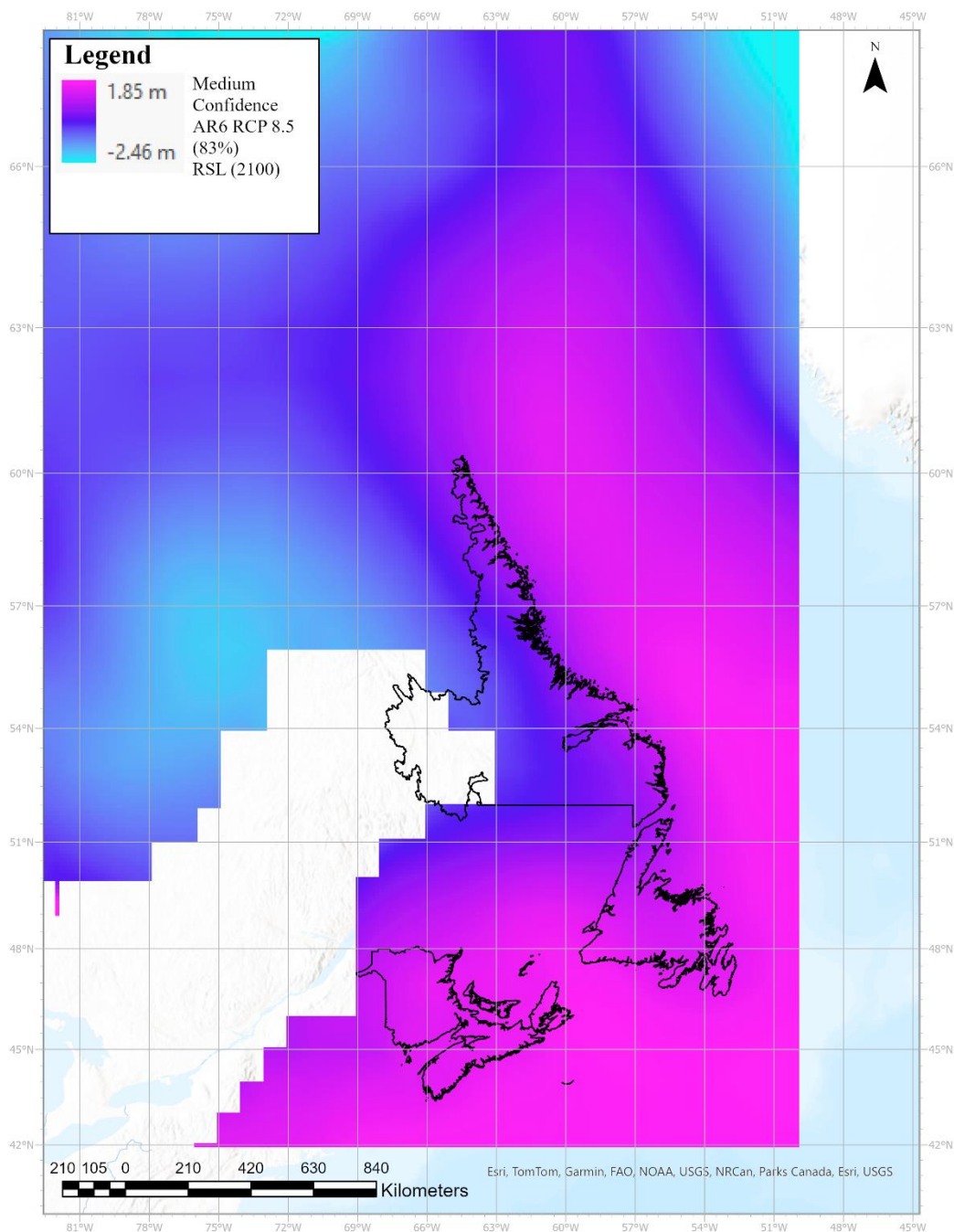
Figure 3 The Zhang & Sheng (2013) 100-year return storm surge grid.

AGRGR originally agreed with CLIMAtlantic to use upper confidence (95%) AR5 RCP 8.5 RSL (James *et al*, 2021) projections to build flood layers for 2050, 2100, and 2150. An amendment to the original agreement changed the RSL input layers to those produced by James & Brierley Green (in prep) using the IPCC AR6 report. AGRGR used the medium confidence (83%) AR6 SSP5-8.5 RSL layers for 2050, 2100, and 2150 to produce flood layers for those years. Medium confidence (83%) AR6 SSP5-8.5 RSL projections are in close agreement with upper confidence (95%) RCP 8.5 AR5 RSL projections in the year 2050 but deviate further above upper confidence (95%) RCP 8.5 AR5 RSL estimates in the years 2100 and 2150 (Table 3). Upper confidence (95%) AR5 RCP 8.5 RSL grids were not produced for the year 2150 in the James *et al* (2021) AR5 report. AGRGR interpolated upper confidence (95%) AR5 RCP 8.5 RSL values for the year 2150 by deriving a linear trend between 2050 and 2100 projections.

**Table 3** Selected locations within Atlantic Canada were used to compare upper confidence (95%) AR5 RCP 8.5 RSL projections with medium confidence (83%) AR6 SSP5-8.5 RSL projections. Medium confidence (83%) AR6 SSP5-8.5 RSL projection data tends to agree with upper confidence (95%) AR5 RCP 8.5 RSL data in the year 2050 with an average difference of -1.1 cm. Medium confidence (83%) AR6 SSP5-8.5 RSL projection data tends to deviate further above upper confidence (95%) AR5 RCP 8.5 RSL predictions in 2100 and 2150, with an average difference of 13.7 cm and 35.5 cm, respectively.

	2050 difference (cm) (AR6 – AR5)	2100 difference (cm) (AR6 – AR5)	2150 difference (cm) (AR6 – AR5)
Northumberland Strait	- 2.2	+ 18.6	+ 44.2
Bay of Fundy	- 3.0	+ 10.7	+ 30.2
Saint John’s	+ 1.1	+ 13.5	+ 34.9
Halifax	- 5.5	+ 2.0	+ 20.0
Minas Basin	- 3.1	+ 9.0	+ 30.6
Chaleur Bay	- 3.2	+ 8.9	+ 30.0
Cabot Strait	- 3.7	+ 10.7	+ 33.5
Placentia Bay	- 0.8	+14.3	+ 36.0
White Bay	+ 0.3	+ 15.7	+ 38.2
Nain	+ 7.6	+ 30.5	+ 56.4
Goose Bay	6.3	+ 24.2	+ 47.8
Hebron	- 0.7	+ 16.1	+ 33.7
Canso	- 2.8	+ 10.3	+ 33.6
Mirimichi	- 6.0	+ 6.7	+ 28.6
<b>Average</b>	- 1.1	+ 13.7	+ 35.5

Medium confidence (83%) AR6 SSP5-8.5 RSL layers were provided in NetCDF format before conversion to raster geo-tiffs in ArcGIS Pro with a geographic coordinate system (latitude/longitude) and a pixel resolution of  $0.1000 \times 0.1000$  degrees ( $12906.2 \times 12906.2$  m) (Figure 4). The source NetCDF files were projected to the Custom Mercator Atlantic Canada projection (Appendix 1).



**Figure 4** The medium confidence (83%) AR6 SSP5-8.5 RSL grid for 2100 provided by James & Brierley-Green (in prep) relative to CGVD 2013.

The Higher High Water Large Tide (HHWL) data used in this work (CHS, 2015) were processed to a raster geo-tiff with a source pixel resolution of  $0.00097 \times 0.00097$  degrees ( $95.4 \times 95.4$  m) (Figure 5). The raster data were derived from Hydrographic vertical separation surfaces for Canadian waters (HyVSEPs) which were constructed by the Canadian Hydrographic Service in partnership with the Canadian Geodetic Service (2015) as defined by Robin *et al.*, (2015). The HyVSEP surfaces map tide level and hydrographic datums to NAD83 on the CGVD2013 geoid using a combination of ocean models, GNSS observations, sea level trends, and satellite altimetry (Robin *et al.*, 2015). AGRG leveraged the HyVSEP surface to incorporate HHWL, defined as the average of the highest high tides, 1 from each of 19 years of predictions, in our flood mapping models to simulate flood events involving the highest tides. The HHWL grid was provided in NAD83 CSRSv7 geographic before it was projected to the custom Mercator Atlantic Canada projection (Appendix 1).

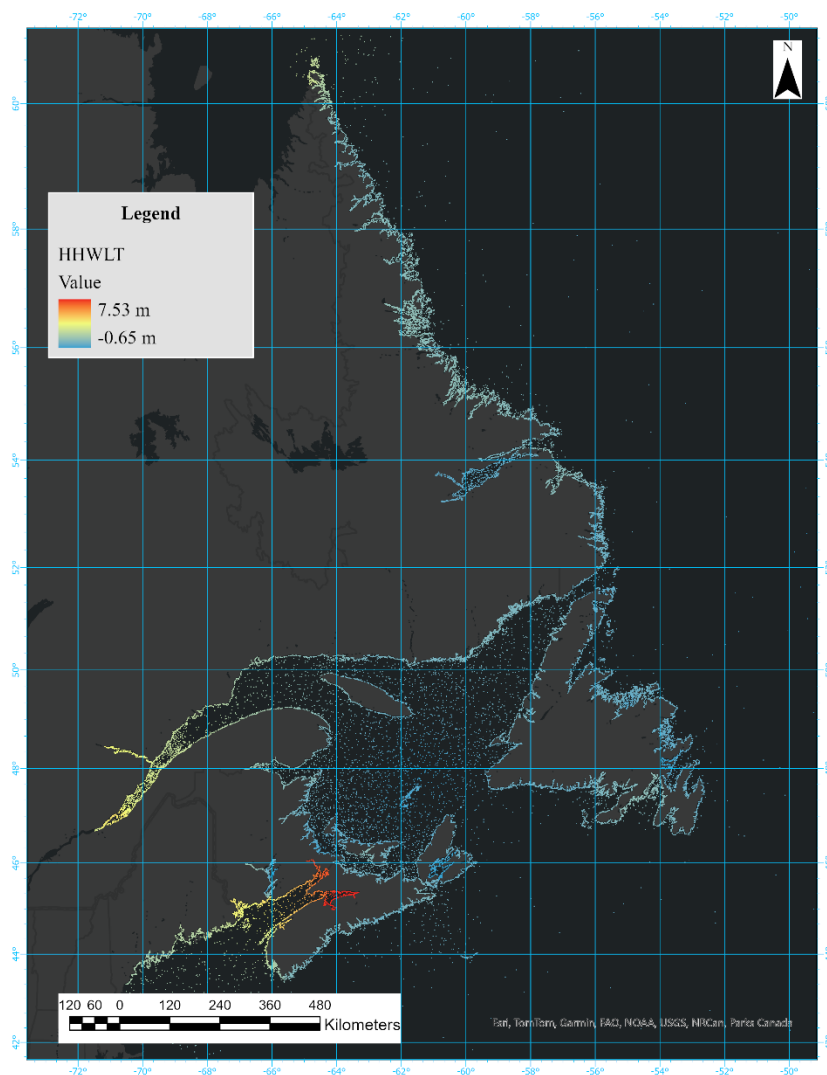


Figure 5 The HHWL raster grid file processed from the Canadian Hydrographic Service (2015) HyVSEP point data.

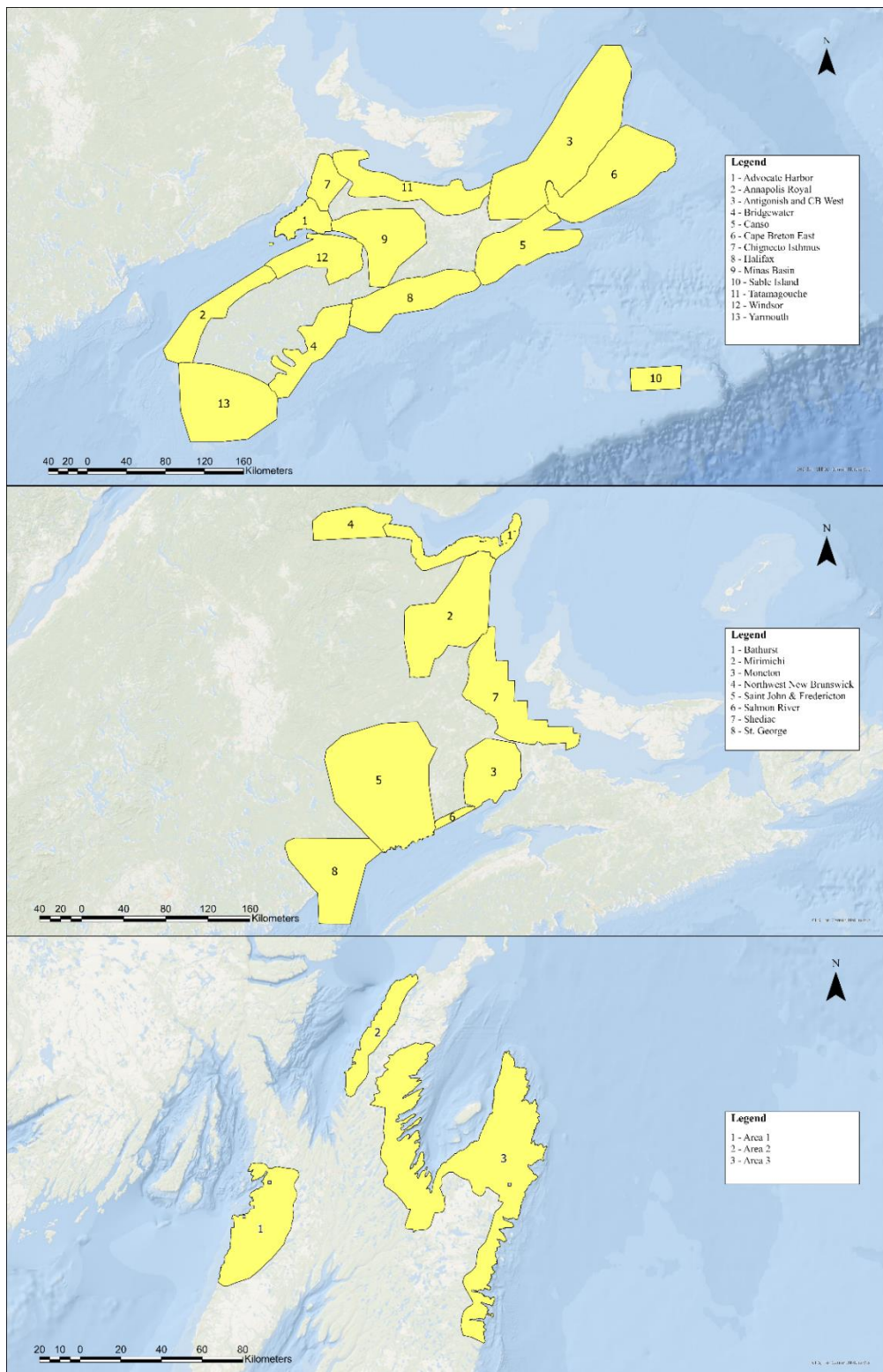
AGRGR used the best available DEMs to derive flood products integrating RSL, storm surge, and HHWLT. Lidar derived DEMs were available for Nova Scotia, New Brunswick, PEI, Les Îles-de-la-Madeleine, and portions of NFLD (Appendix 1). All lidar DEMs had a  $1 \times 1$  m pixel resolution. Lidar DEM data covering New Brunswick and PEI were sourced in NAD83 CSRS UTM Zone 20N, whereas lidar data covering portions of Newfoundland were provided in WGS 1984 Web Mercator (auxiliary sphere). The original projection of lidar data covering Nova Scotia was NAD83 (CSRS) v6 UTM Zone 20N. Lidar data covering Nova Scotia and parts of New Brunswick were constructed at AGRGR, whereas the [HRDEM – CanElevation Series](#) (NRCAN, 2024) provided all lidar DEM data for PEI, additional portions of New Brunswick, and parts of Newfoundland. Les Îles-de-la-Madeleine lidar DEM data were provided by Solomon (2024) in NAD83 CSRS MTM 4. Lidar derived DEM data were unavailable for much of NFLD. As such, AGRGR substituted lidar with the CDEM provided by the Government of Canada at a  $20 \times 20$  m pixel resolution, defined in NAD 1983 (CSRS). The CDEM stems from the existing Canadian Digital Elevation Data (CDED). The latter were extracted from the hypsographic and hydrographic elements of the National Topographic Data Base (NTDB) at the scale of 1:50 000, the Geospatial Database (GDB), various scaled positional data acquired by the provinces and territories, or remotely sensed imagery. In the CDEM data, elevations can be either ground or reflective surface elevations. The CDEM data covers the Canadian Landmass. The typical vertical accuracy of the CDEM ranges from 2 – 17 m. All DEMs were reprojected to the custom Mercator Atlantic Canada projection (Appendix 1).

Post Hurricane Fiona wrack line elevation data were acquired using high precision GNSS rovers with a vertical accuracy of  $\pm 2$  cm. Wrack line elevation data were received from an agglomeration of sources including AGRGR (2023), Jardine Consulting (2023), and Dominique Bérubé (2023). Wrack line location was approximated by identifying the elevation of washed-up material along the coastline impacted by Hurricane Fiona. AGRGR received wrack line observation data covering the coastline of PEI in NAD83 (CSRS) v7 (Figure 2). Wrack line data received from New Brunswick extended along the coastline from Pokeshaw to Tidnish Bridge and were defined in NAD83 CSRS New Brunswick Stereographic. Data acquired for Nova Scotia were defined in NAD83 CSRS UTM Zone 20N and spanned the Nova Scotian coastline from Tidnish Bridge to Inverness (Figure 2). Data received covering Newfoundland were limited to Port Aux Basques and were defined in NAD83 CSRS UTM Zone 21N (Figure 2). All wrack line data were reprojected to the custom Mercator Atlantic Canada projection (Appendix 1).

## 2.1 DATA PRE-PROCESSING

The custom Mercator Atlantic Canada (MAC) projection was applied to all raw layers used in this project (Appendix 1). The MAC coordinate system used a Mercator projection. The central meridian of the MAC projection was at  $-56^{\circ}$  with a standard parallel at  $46^{\circ}$ . The MAC projection centralized raw input layers on Atlantic Canada, minimizing the stretching inherent with the geographic latitudinal/longitudinal coordinate systems belonging to many of the raw grid files. Projecting the grids to MAC also defined the linear unit (meters), simplifying processing methods. NAD83 CSRS v7 was the horizontal datum applied to all layers in the project and the vertical datum used was CGVD 2013.

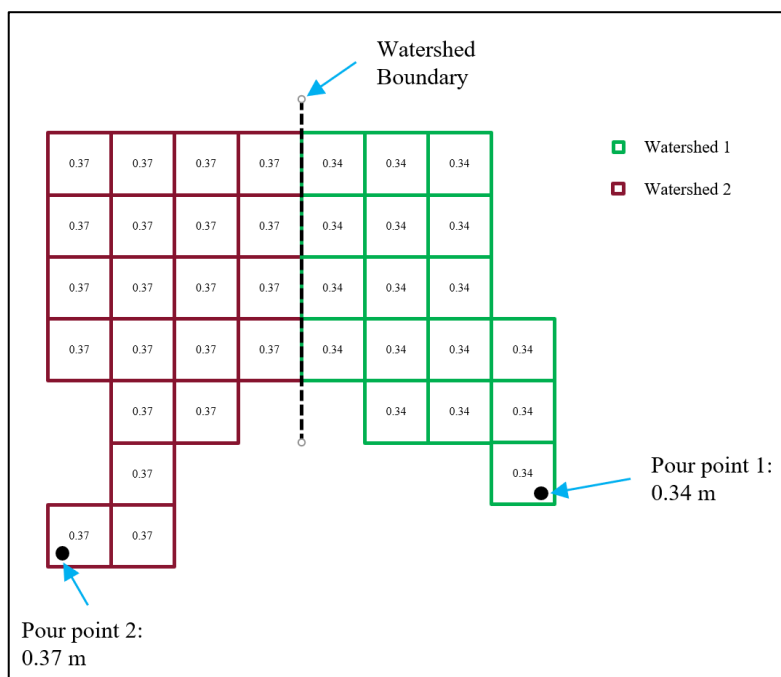
Storm surge, RSL, and HHWLT data layers were resampled using a variety of techniques in ArcGIS Pro and Python to match the resolution of the underlying DEM data. This necessary step was executed to ensure resulting flood layers preserved the detail of the DEM data. Atlantic Canada data, apart from most of Newfoundland and all of Labrador where DEM data was much coarser ( $20\text{ m} \times 20\text{ m}$ ), were divided into county scale chunks for processing (Figure 6). PEI and Les Îles-de-la-Madeleine were processed as individual zones. Lidar DEMs were clipped to each zone along with the input RSL, storm surge, and HHWLT data layers.



**Figure 6** The processing zones used in this project. Lidar DEM coverage in Nova Scotia, New Brunswick, and Newfoundland was divided into smaller scale chunks for processing.

Medium confidence (83%) AR6 SSP5-8.5 RSL grids were interpolated using a spline with barriers technique coupled with bilinear resampling events. Each grid was clipped to a predefined processing region and resampled by a factor of 100 to a finer pixel resolution ( $129.062 \times 129.062$  m) using a bilinear resampling method. Resampled grids were passed into a spline tool incorporating watershed boundaries as interpolation barriers. Watershed shapefiles were acquired from GeoNB (2023) for New Brunswick. Watershed boundaries were derived using spatial analyst tools in ArcGIS Pro for other regions including Nova Scotia, PEI, Les Îles-de-la-Madeleine, and NFLD. RSL grid outputs from the spline tool were resampled to a  $1 \times 1$  m pixel resolution using a bilinear interpolation method. The methods used to pre-process the RSL grids were executed in ArcGIS Pro and a standalone Python script.

HHWLT and Storm surge grids were processed using a watershed methodology developed at AGRG (McGuigan, pers comm). A standalone Python script was developed containing the tools necessary to execute the watershed procedure. A clipping operation to the area of interest (AOI), followed with a bilinear resampling event initiated the procedure, reducing pixel resolution of source grids to  $5 \times 5$  m. Resampled grids were converted to point feature classes and, along with the DEM of each AOI, were input to the watershed analysis tool provided by ESRI. In this context the watershed analysis tool determined the pixels in the DEM contributing to the nearest hydrologically connected point (pour point) within the input shapefile (Figure 7). The elevation value of the pour point was adopted by the pixels within the contributing watershed. Watershed raster outputs were resampled to a final resolution of  $1 \times 1$  m using a bilinear interpolation method.

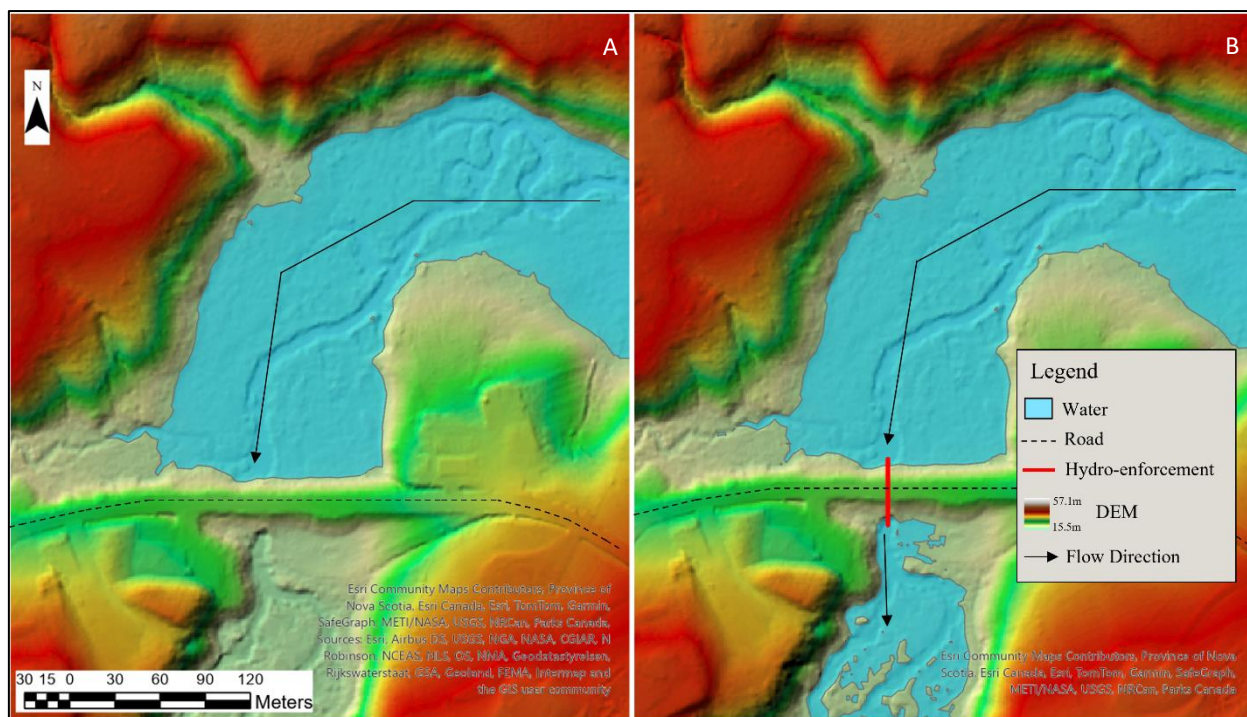


**Figure 7** This illustration describes the watershed methodology whereby pixels belonging to each watershed were assigned the value of the nearest pour point.

Raw Hurricane Fiona wrack line data covering New Brunswick and PEI were received in .csv format, whereas data covering Nova Scotia were provided as a point shapefile. Files covering New Brunswick and PEI were converted to point shapefiles in ArcGIS Pro. Each shapefile was projected to the MAC projection. Shapefiles were organized and processed in groups with respect to the data provider.

#### HYDRO ENFORCEMENT METHODS

All DEMs were hydrologically connected (hydro enforced) by burning in hydrological pathways. Hydrological pathways are any locations in the DEM where a culvert, causeway, or river crossing exists, excluding aboiteau, hydro-dam, or other manmade structures that inhibit the flow of water (Figure 8). Hydrological pathways allow and direct the flow of water, defining the realized extent of flood plains in many cases. The importance of hydrological connectivity with respect to accurate flood mapping necessitated the identification of hydrological pathways within DEM data. Hydrological pathways were manually identified and drawn in ArcGIS Pro for the majority of Atlantic Canada. A standalone Python script was developed part way through the project to assist with hydrological pathway detection and generation. Hydrological pathways were built as line shapefiles before conversion to binary raster layers. The pathways were burned into the DEM using a raster calculation, simulating hydrological connectivity where flow channels existed.



**Figure 8** This graphic illustrates the process used to hydrologically condition the DEM. Panel A shows an inundated stream that stops at a roadway present in the DEM because there is no hydro-enforcement line. Panel B shows that water in the stream will flow under the road within the DEM when the hydro-enforcement line is present.

## 3 FLOOD PRODUCTS GENERATION

## VECTOR FLOOD LAYER GENERATION

The general approach taken to generate the flood layers involved adding the processed storm surge, RSL, and HHWLT grids with the appropriate wave run-up value forming a water level raster layer that was conditionally subtracted from the hydrologically conditioned DEM within a raster calculator operation (Figure 8). The conditional logic applied in the raster calculation identified pixels within the DEM below the elevation of the water level raster layer and converted selected pixels to a binary raster file. The binary raster files were vectorized to build shapefiles representing each flood scenario. Vector shapefiles were selected based on their hydrological connectivity to the ocean, excluding unconnected polygons from the output flood shapefile. Final flood shapefiles (Figure 9) were smoothed to eliminate acute vertex junctions. The process was executed using a script developed in Python which integrated various geoprocessing tools available from the arcpy Python library.

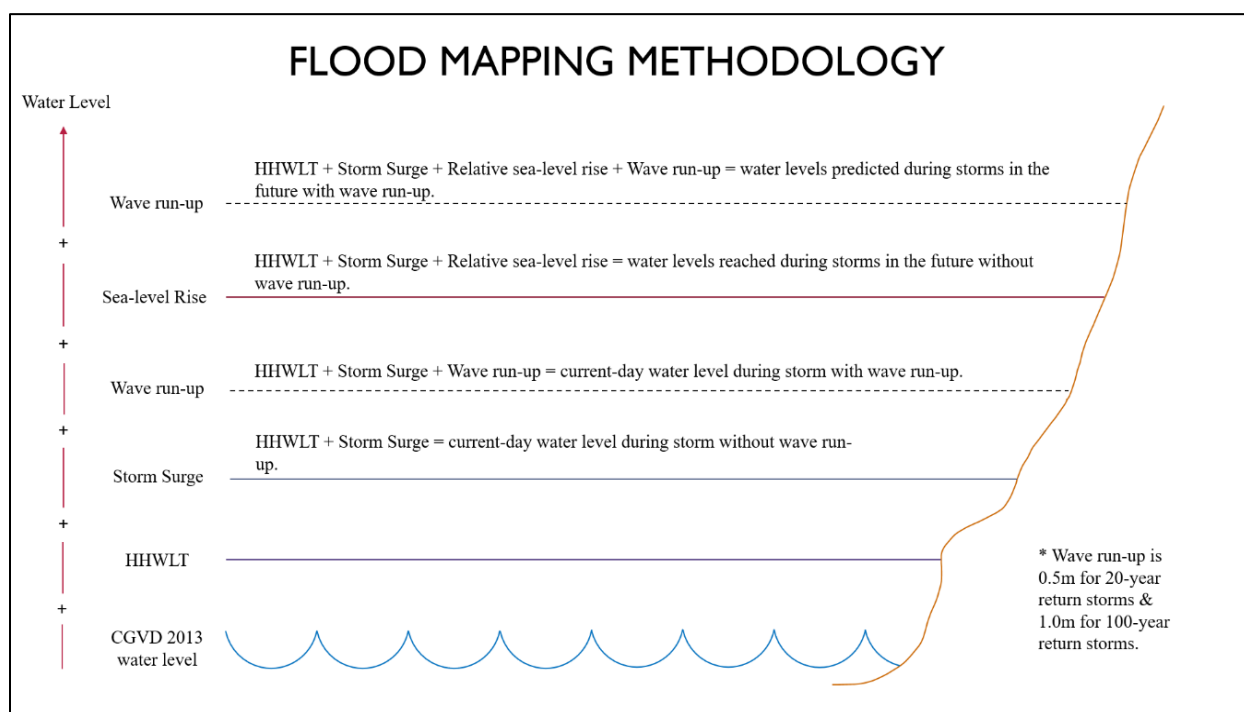
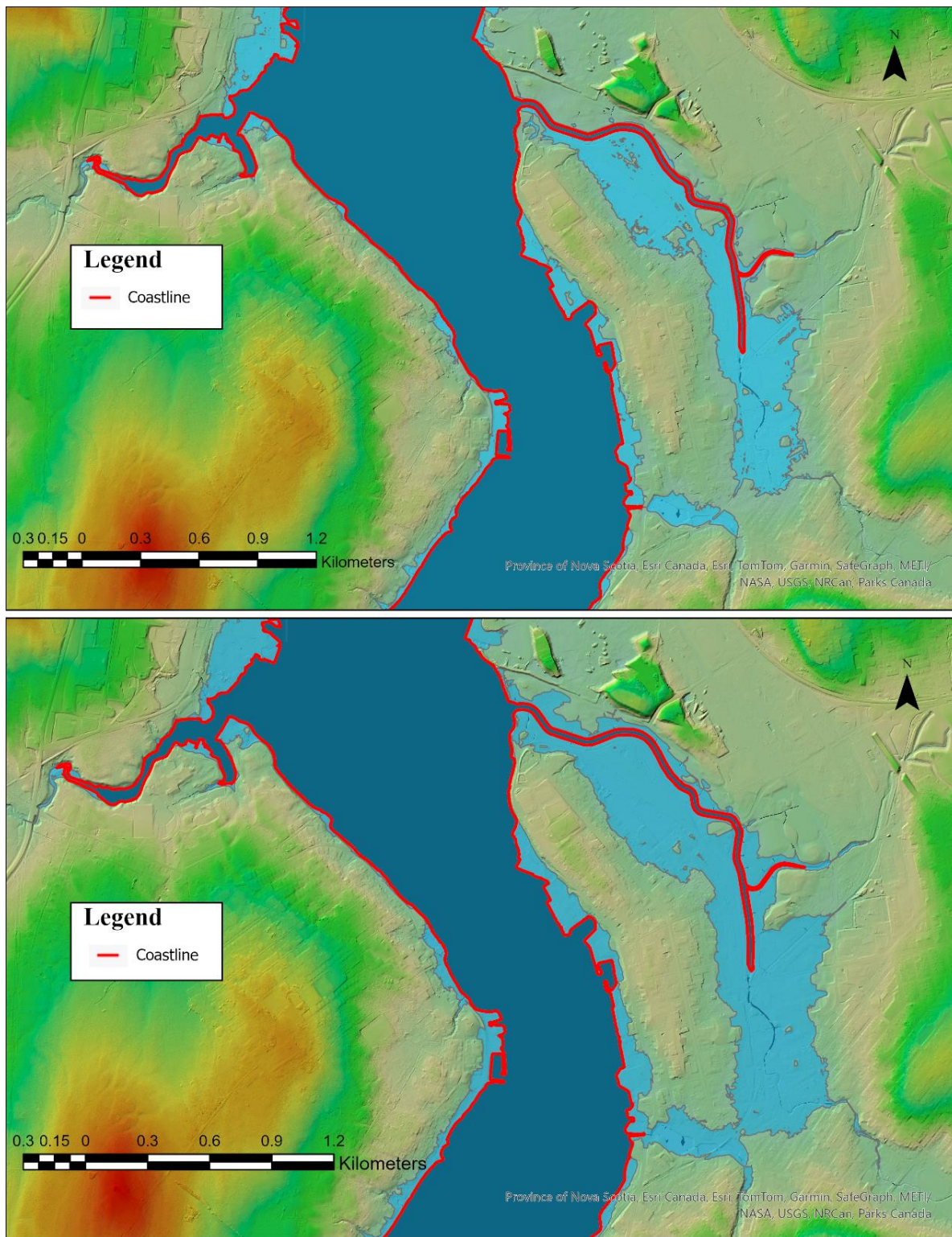


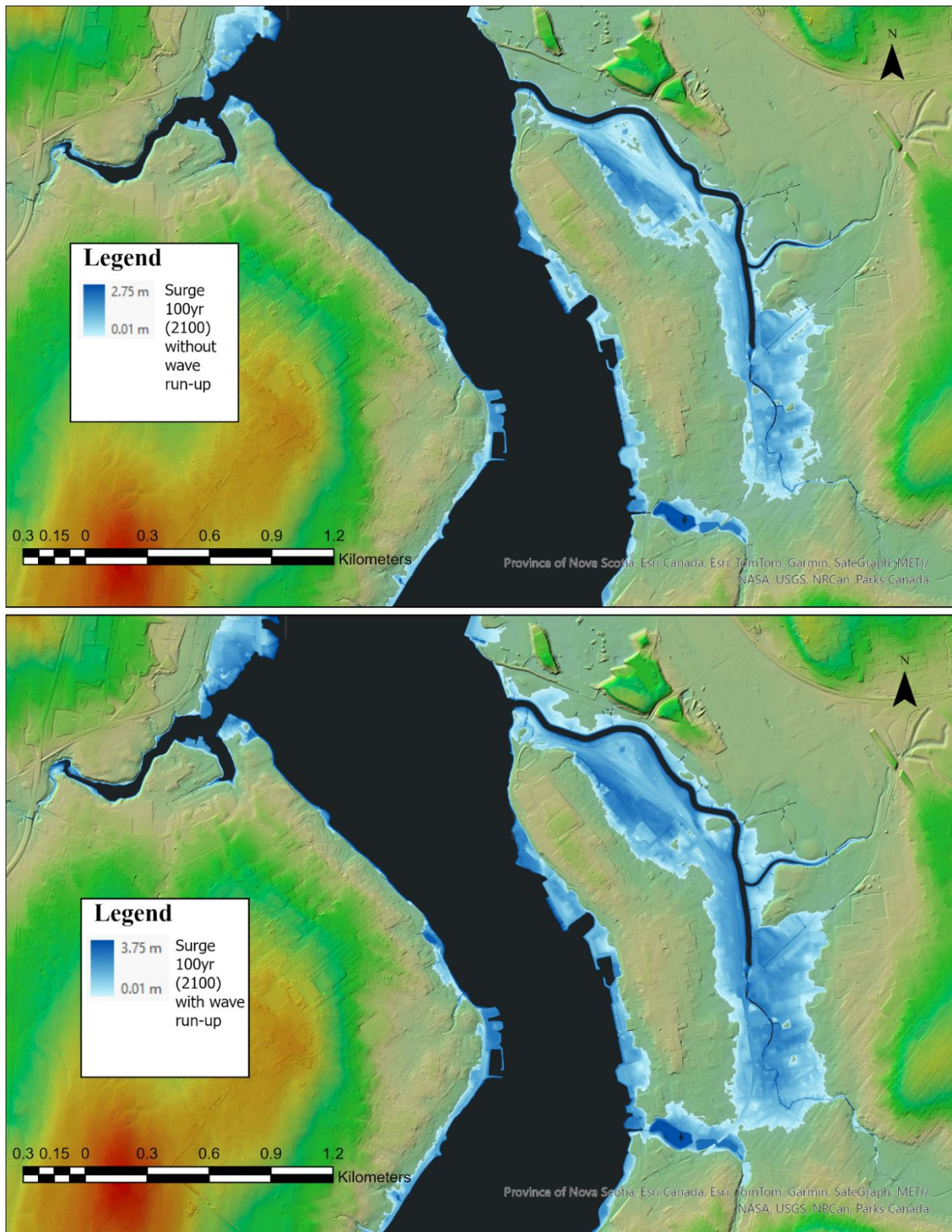
Figure 9 The above graphic depicts the method used to generate the flood layers in this project.



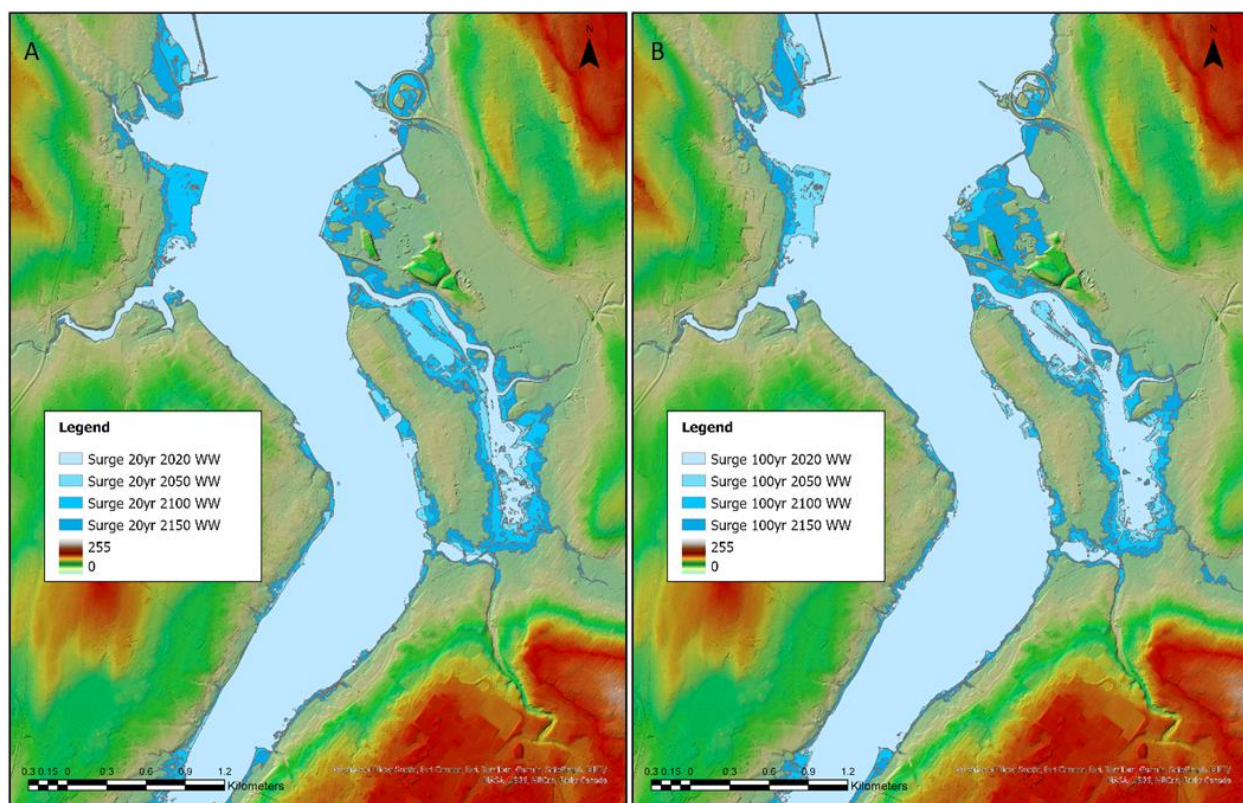
**Figure 10** The 100yr return storm event flood layers for year 2100 centered on Sydney, Nova Scotia. The top map frame displays the 'without wave run-up' variant and the bottom map frame displays the 'with wave run-up' (+ 1.0 m) variant.

## FLOOD DEPTH RASTER GENERATION

Flood depth raster layers were produced in another raster calculator operation which added storm surge, RSL, and HHWLT grids together with the appropriate wave run-up value to form a water level raster that was conditionally subtracted from the hydrologically conditioned DEM. The conditional calculation selected DEM pixels below the elevation of the water level raster and subtracted the pixel value of the overlying water level raster from selected DEM pixels, building a separate raster layer which stored the flood depth information. Outputs from the operation were clipped to the matching vector shapefile to exclude non-hydro-connected pixels. Final flood depth raster layers (Figure 10) were constructed using LZW compression, a lossless compression algorithm applied to reduce file size. As the water surface within the DEMs used in this project was not cleaned, there may be some artifacts present in the flood depth raster layers as a result. The process was executed using a script developed in Python.

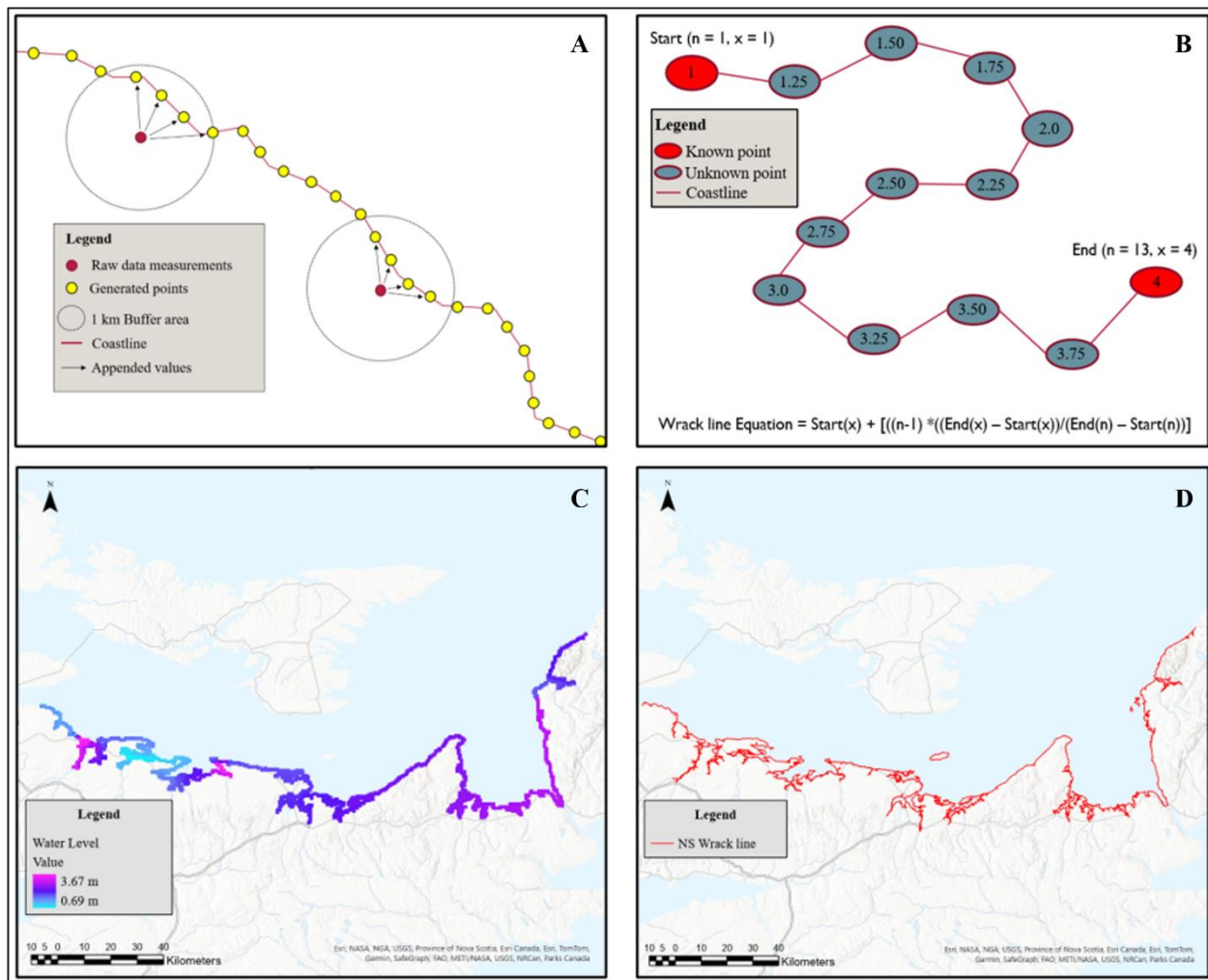


**Figure 11** The 100yr return storm event raster flood depth layers for year 2100 centered on Sydney, Nova Scotia. The top map frame displays the 'without wave run-up' variant whilst the bottom map frame displays the 'with wave run-up' (+ 1.0 m) variant.



**Figure 12** This depiction, centered on Sydney, Nova Scotia, displays flood layers produced using 20-year return storm surge grids (A) compared with flood layers produced using 100-year return storm surge grids (B). Flood layers in (A) have an additional 0.5 m wave run-up value incorporated and flood layers in (B) have an extra 1.0 m wave run-up value added.

The Hurricane Fiona wrack line was derived from point source elevation values using the network analysis toolbox in ArcGIS Pro to order known elevation points along the coastline. Additional points were generated along the coastline at 1km intervals to fill gaps in source data. If the additional points fell within 1km of a known wrack line elevation point, the value of the known wrack line point was appended to the generated point. Elevation values for additional points outside of the 1km buffer of known wrack line points were calculated using an interpolation algorithm which estimated the elevation of generated points based on the value of the two nearest known wrack line points (Figure 12). The formula applied to ascertain interpolated elevation values was in the form  $[Start(x) + (((n-1) * ((End(x) - Start(x)) / (End(n) - Start(n))))]$ , where (x) represents the elevation value and (n) represents the point number in sequence along the line. This calculation was iteratively executed for each interpolated point using a script developed in Python. The final point shapefile was converted to a raster layer in ArcGIS Pro. DEM pixel values below those in the wrack line raster were selected and extracted as a binary raster layer using a conditional statement executed by the raster calculator in ArcGIS Pro. A polygon conversion was performed on the binary raster layer before creating a line shapefile of the innermost extent reached by the inundation polygon. The final line shapefile was cleaned and smoothed to eliminate any acute vertex junctions.



**Figure 13** This figure outlines the workflow used to derive a Hurricane Fiona wrack line from raw data observations. Panel (A) illustrates that elevation values stored in raw data measurements (red points) were appended to points (yellow points) generated along the coastline (red line) that were within a 1km buffer area (black circle). Panel (B) describes the interpolation algorithm used to derive elevation values at unknown points (blue) that fell outside of the 1km buffer around known points (red). Panel (C) highlights the raster layer that was created when the interpolated point file was converted to a raster geo-tiff. Panel (D) displays the final wrack line file that was created from the polygon product derived from the conditional raster calculation executed to select DEM pixels below the elevation of the wrack line raster layer. Please be advised that the illustrations shown above are not to drawn to scale and are only intended to aid with the understanding of the project methods.

#### 4 CONCLUDING REMARKS

AGRG completed all flood layers and the Hurricane Fiona wrack line requested by CLIMATlantic. CLIMATlantic received vector flood layers and raster flood depth layers covering Atlantic Canada for all flooding scenarios considered in the project. CLIMATlantic also received the Hurricane Fiona wrack line and all hydrologically connected DEMs produced in this project. All deliverables were uploaded to a hard drive and delivered to CLIMATlantic.

This project represents the first ever development of flood layers that cover the entire extent of Atlantic Canada. AGRG devised an original method to develop flood products incorporating storm surge, HHWLT, and RSL to better equip Atlantic Canada with data that will help achieve improved flood prediction and preparedness. A novel method was devised to produce the Hurricane Fiona wrack line which incorporated wrack line measurements collected from point sources around Atlantic Canada. AGRG hopes the results of this work will inform maritime management decisions around Atlantic Canada, safeguarding our citizens, infrastructure, and our coastal economy. We firmly believe that the continuation and improvement of coastal data acquisition will serve to enhance future studies of this nature, enabling more accurate flood prediction and coastal management.



Appendix 1 This table contains the projection information of all raw data and the final Custom Mercator Atlantic Canada projection.

<p><b>Final Projection</b></p> <p>Projected Coordinate System Mercator_Atlantic_Canada</p> <p>Projection Custom</p> <p>Authority Meters (1.0)</p> <p>Linear Unit 0.0</p> <p>False Easting 0.0</p> <p>False Northing -56.0</p> <p>Central Meridian 46.0</p> <p>Standard Parallel 1 0.0</p> <p>Geographic Coordinate System GCS_NAD83_CSRS_v7</p> <p>WKID 0</p> <p>Authority (0.0174532925199433)</p> <p>Angular Unit Degree Greenwich (0.0)</p> <p>Prime Meridian North American Datum of 1983 (CSRS) version 7</p> <p>Datum GRS 1980</p> <p>Spheroid 6378137.0</p> <p>Semimajor Axis 6356752.314140356</p> <p>Seminor Axis 298.25722101</p>	<p><b>Les Îles-de-la-Madeleine Lidar DEMs</b></p> <p>Projected Coordinate System NAD 1983 CSRS MTM 4</p> <p>Projection Transverse Mercator</p> <p>WKID 2946</p> <p>Previous WKID 2141</p> <p>Authority EPSG</p> <p>Linear Unit Meters (1.0)</p> <p>False Easting 304800.0</p> <p>False Northing 0.0</p> <p>Central Meridian -61.5</p> <p>Scale Factor 0.9999</p> <p>Latitude Of Origin 0.0</p> <p>Geographic Coordinate System NAD 1983 (CSRS)</p> <p>WKID 4617</p> <p>Previous WKID 4140</p> <p>Authority EPSG</p> <p>Angular Unit Degree (0.0174532925199433)</p> <p>Prime Meridian Greenwich (0.0)</p> <p>Datum D North American 1983 CSRS</p> <p>Spheroid GRS 1980</p> <p>Semimajor Axis 6378137.0</p> <p>Seminor Axis 6356752.314140356</p> <p>Inverse Flattening 298.25722101</p>
<p><b>Storm Surge Grids (Zhang &amp; Sheng, 2013)</b></p> <p>Geographic Coordinate System GCS_NAD83_CSRS_v7</p> <p>WKID 0</p> <p>Authority (0.0174532925199433)</p> <p>Angular Unit Degree Greenwich (0.0)</p> <p>Prime Meridian North American Datum of 1983 (CSRS) version 7</p> <p>Datum GRS 1980</p> <p>Spheroid 6378137.0</p> <p>Semimajor Axis 6356752.314140356</p> <p>Seminor Axis 298.25722101</p> <p>Inverse Flattening</p>	<p><b>Prince Edward Island Wrack Line Data</b></p> <p>Geographic Coordinate System NAD 1983 (CSRS) v7</p> <p>WKID 8255</p> <p>Authority EPSG</p> <p>Angular Unit Degree (0.0174532925199433)</p> <p>Prime Meridian Greenwich (0.0)</p> <p>Datum North American Datum of 1983 (CSRS) version 7</p> <p>Spheroid GRS 1980</p> <p>Semimajor Axis 6378137.0</p> <p>Seminor Axis 6356752.314140356</p> <p>Inverse Flattening 298.25722101</p>
<p><b>HHWLT Grid (Canadian Hydrographic Service, 2015)</b></p> <p>Geographic Coordinate System GCS_NAD83_CSRS_v7</p> <p>WKID 0</p> <p>Authority (0.0174532925199433)</p> <p>Angular Unit Degree Greenwich (0.0)</p> <p>Prime Meridian North American Datum of 1983 (CSRS) version 7</p> <p>Datum GRS 1980</p> <p>Spheroid 6378137.0</p> <p>Semimajor Axis 6356752.314140356</p> <p>Seminor Axis 298.25722101</p> <p>Inverse Flattening</p>	<p><b>New Brunswick Wrack Line Data</b></p> <p>Projected Coordinate System NAD 1983 CSRS New Brunswick Stereographic</p> <p>Projection Double Stereographic</p> <p>WKID 2953</p> <p>Previous WKID 2036</p> <p>Authority EPSG</p> <p>Linear Unit Meters (1.0)</p> <p>False Easting 2500000.0</p> <p>False Northing 7500000.0</p> <p>Central Meridian -66.5</p> <p>Scale Factor 0.999912</p> <p>Latitude Of Origin 46.5</p> <p>Geographic Coordinate System NAD 1983 (CSRS)</p> <p>WKID 4617</p> <p>Previous WKID 4140</p> <p>Authority (0.0174532925199433)</p> <p>Angular Unit Degree Greenwich (0.0)</p> <p>Prime Meridian D North American 1983 CSRS</p> <p>Datum GRS 1980</p> <p>Spheroid 6378137.0</p> <p>Semimajor Axis 6356752.314140356</p> <p>Seminor Axis 298.25722101</p> <p>Inverse Flattening</p> <p>Vertical Coordinate System CGVD2013a(2010) height</p> <p>WKID 9245</p> <p>Authority EPSG</p> <p>Linear Unit Meters (1.0)</p> <p>Direction positive up</p> <p>Vertical Shift 0.0</p> <p>Vertical Datum Canadian Geodetic Vertical Datum of 2013 CGG2013a</p>
<p><b>New Brunswick &amp; PEI Lidar DEMs &amp; Nova Scotia wrack line observations</b></p> <p>Projected Coordinate System NAD 1983 CSRS UTM Zone 20N</p> <p>Projection Transverse Mercator</p> <p>WKID 2961</p> <p>Previous WKID 2038</p> <p>Authority EPSG</p> <p>Linear Unit Meters (1.0)</p> <p>False Easting 500000.0</p> <p>False Northing 0.0</p> <p>Central Meridian -63.0</p> <p>Scale Factor 0.9996</p> <p>Latitude Of Origin 0.0</p> <p>Geographic Coordinate System NAD 1983 (CSRS)</p> <p>WKID 4617</p> <p>Previous WKID 4140</p> <p>Authority EPSG</p> <p>Angular Unit Degree (0.0174532925199433)</p> <p>Prime Meridian Greenwich (0.0)</p> <p>Datum D North American 1983 CSRS</p> <p>Spheroid GRS 1980</p> <p>Semimajor Axis 6378137.0</p> <p>Seminor Axis 6356752.314140356</p> <p>Inverse Flattening 298.25722101</p>	<p><b>Newfoundland Wrack Line Data</b></p> <p>Projected Coordinate System NAD 1983 CSRS UTM Zone 21N</p> <p>Projection Transverse Mercator</p> <p>WKID 2962</p> <p>Previous WKID 2148</p> <p>Authority EPSG</p> <p>Linear Unit Meters (1.0)</p> <p>False Easting 500000.0</p> <p>False Northing 0.0</p> <p>Central Meridian -57.0</p> <p>Scale Factor 0.9996</p> <p>Latitude Of Origin 0.0</p> <p>Geographic Coordinate System NAD 1983 (CSRS)</p> <p>WKID 4617</p> <p>Previous WKID 4140</p> <p>Authority EPSG</p> <p>Angular Unit Degree (0.0174532925199433)</p> <p>Prime Meridian Greenwich (0.0)</p> <p>Datum D North American 1983 CSRS</p> <p>Spheroid GRS 1980</p> <p>Semimajor Axis 6378137.0</p> <p>Seminor Axis 6356752.314140356</p> <p>Inverse Flattening 298.25722101</p>
<p><b>Newfoundland Lidar DEMs</b></p> <p>Projected Coordinate System WGS 1984 Web Mercator (auxiliary sphere)</p> <p>Projection Mercator Auxiliary Sphere</p> <p>WKID 3857</p> <p>Previous WKID 102100</p> <p>Authority EPSG</p> <p>Linear Unit Meters (1.0)</p> <p>False Easting 0.0</p> <p>False Northing 0.0</p> <p>Central Meridian 0.0</p> <p>Standard Parallel 1 0.0</p> <p>Auxiliary Sphere Type 0.0</p> <p>Geographic Coordinate System WGS 1984</p> <p>WKID 4326</p> <p>Authority EPSG</p> <p>Angular Unit Degree (0.0174532925199433)</p> <p>Prime Meridian Greenwich (0.0)</p> <p>Datum D WGS 1984</p> <p>Spheroid WGS 1984</p> <p>Semimajor Axis 6378137.0</p> <p>Seminor Axis 6356752.314245179</p> <p>Inverse Flattening 298.257223563</p>	<p><b>Newfoundland and Labrador CDEM</b></p> <p>Geographic Coordinate System NAD 1983 (CSRS)</p> <p>WKID 4617</p> <p>Previous WKID 4140</p> <p>Authority EPSG</p> <p>Angular Unit Degree (0.0174532925199433)</p> <p>Prime Meridian Greenwich (0.0)</p> <p>Datum D North American 1983 CSRS</p> <p>Spheroid GRS 1980</p> <p>Semimajor Axis 6378137.0</p> <p>Seminor Axis 6356752.314140356</p> <p>Inverse Flattening 298.25722101</p>