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OCEAN NETWORKS CANADA

Haida Gwaii Erosion Study
Appendix: Digital Elevation Models Metadata Report

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1.0 Summary

Ocean Networks Canada (ONC) has joined Northwest Hydraulic Consultants Ltd. (NHC) to aid in emergency preparedness for communities in Haida Gwaii, British Columbia. ONC's role in this project was to create integrated topographic bathymetric digital elevation models (DEMs) and tsunami models. This report will specifically discuss the creation of DEMs to support risk and vulnerability assessment, as well as improve collective resiliencies of these coastal communities.

Throughout June 2021 to May 2022, ONC developed DEMs for areas of Haida Gwaii, British Columbia, which included the Village of Masset, Village of Port Clements, Village of Daajing Giids, Sandspit, and Tlell. The purpose of these DEMs was to provide support for modelling of tsunami inundation due to potential earthquakes from the Alaska-Aleutian and Cascadia Subduction Zones as part of the Haida Gwaii Erosion Study for North Coast Regional District (NCRD) in partnership with NHC and the Village of Daajing Giids, the Village of Masset and the Village of Port Clements.

DEMs were created by implementing strategies using international standards developed by the National Center for Environmental Information (NCEI), and National Ocean and Atmospheric Administration (NOAA). ONC participated in several workshops as part of a cross-border collaboration effort to develop these DEM standards. DEM creation is a complex process which aims to create a smooth representation of the surface of the earth from multiple bathymetric and topographic data sources. A high-quality DEM is imperative to this work as even small deviations in elevation, or minor artifacts can significantly affect the quality of the tsunami and flood hazard modelling.

DEM products include three lower resolution grids at 240m, 160m, and 40m horizontal resolution. Higher resolution 10m grids were created in the vicinity of the study areas. 240m DEM was used for the storm wave modelling by NHC as well as tsunami modelling by ONC, and the 160m and 40m DEMs were used to inform the modelling for the four higher resolution 10m horizontal resolution grids, referred to as the "McIntyre Bay" including Masset and Tow Hill, "Masset Inlet" including Port Clements and Juskatla, "Tlell", and "Skidegate Inlet" including Daajing Giids and Sandspit (Figure 1). The DEMs were created from a variety of datasets including recently captured field data using drones and ground survey techniques, acquired to support this project. The extents of these DEMs, the data sources, as well as the data conversion and DEM creation methods are described in this document.

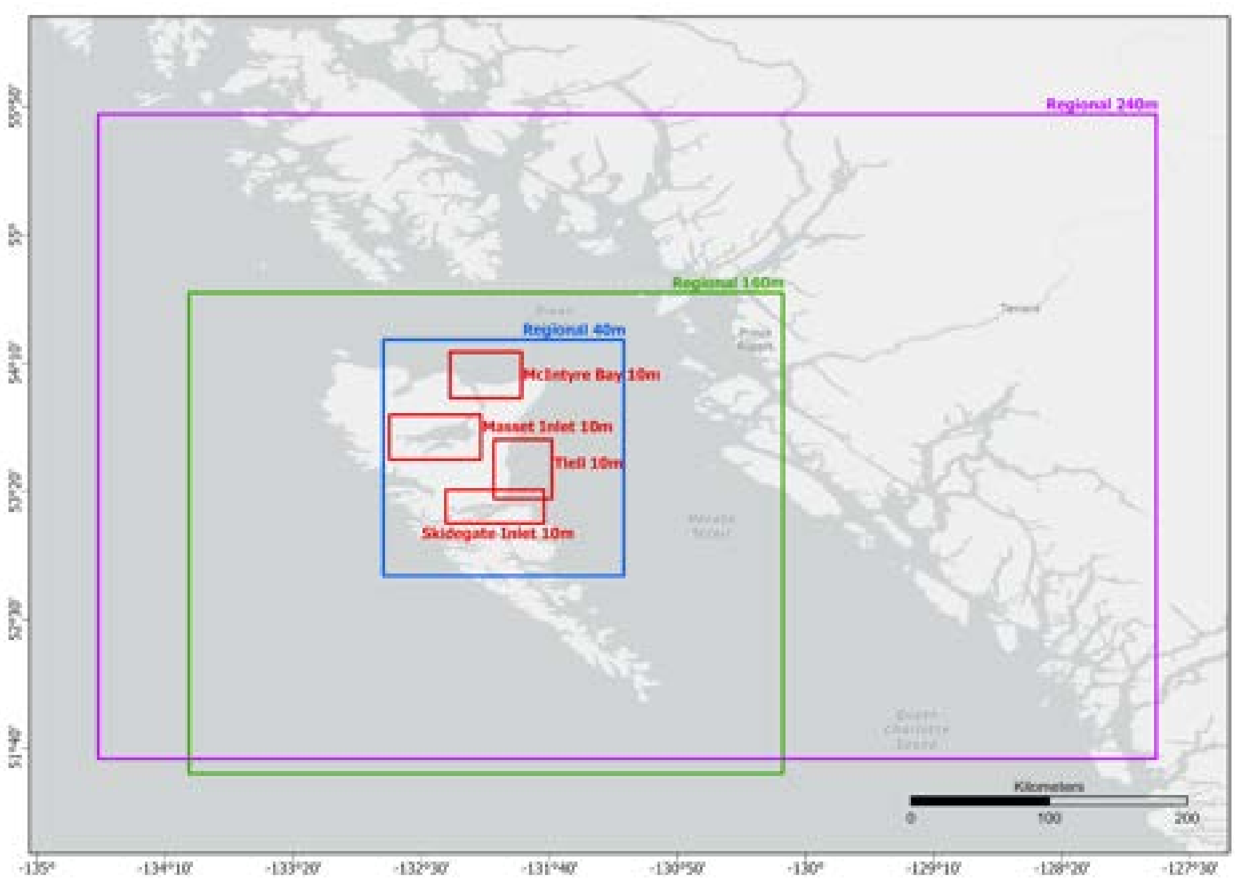

Figure 1. Map showing the extents of the DEMs created for this project.

2.0 DEM Specifications

The lower resolution DEMs were built to the specifications listed in Table 1 and the high resolution DEMs are listed in Table 2.

Table 1. Specifications for the low resolution DEMs			
Grid	Regional 240m	Regional 160m	Regional 40m
Grid Area	Northwest British Columbia and Southwest Alaska	Haida Gwaii including the entirety of Graham and Moresby Islands and surrounding waters	Northeastern Haida Gwaii including Masset Inlet, Port Clements, Tlell, and Daajing Giids
Coverage extent (west/east/ south/north)	-134.601622/-127.72096 /51.59480/55.78243	-134.01047/-130.1490 6/51.49898/54.62170	-132.74636/-131.18388/52 .78374/54.31838
Spatial Resolution	240m	160m	40m
Coordinate System	Geographic Coordinate System World Geodetic System of 1984 (GCS WGS-84)		
Horizontal Datum	World Geodetic System of 1984 (WGS-84)		
Vertical Datum	Canadian Geographic Vertical Datum of 2013 (CGVD2013)		
Vertical Units	Metres		
Data Format	TIFF		

Table 2. Specifications for the high resolution DEMs				
Grid	McIntyre Bay	Masset Inlet	Tlell	Skidegate Inlet
Grid Area	Area surrounding Masset south and east to Tow Hill	Area surrounding southern Masset Inlet including Port Clements and Juskatla	Area on east coast of Haida Gwaii from Skidegate to north Tlell	Area encompassing northeastern Moresby Island and southeastern Graham Island including Daajing Giids and Sandspit
Coverage extent (west/east/ south/north)	-132.31445/-131.84926/53.93839/54.23845	-132.70684/-132.11309/53.53841/53.82880	-132.02904/-131.65115/53.28378/53.66944	-132.34200/-131.70104/53.12400/53.34199
Spatial Resolution	10m			
Coordinate System	Geographic Coordinate System World Geodetic System of 1984 (GCS WGS-84)			
Horizontal Datum	World Geodetic System of 1984 (WGS-84)			
Vertical Datum	Canadian Geographic Vertical Datum of 2013 (CGVD2013)			
Vertical Units	Metres			
Data Format	TIFF			

3.0 Data Sources

The DEMs consist of nine different data sources, as listed in Table 2, that were then integrated into one continuous DEM surface. The Canadian Hydrographic Service (CHS) coastline was used to clip the lower resolution Canada DEM and NOAA data sources so that only the land and bathymetric values, respectively, were preserved as DEM inputs for each. Please refer to pages 31-35 for maps of these datasets.

Table 3. Data Sources					
Source/Title	**Date**	**Data Type**	**Resolution**	**Horizontal Datum**	**Vertical Datum**
Field Data - drone (ungridded), GPS, and echosounder survey (ungridded) at Juskatla	2020	Merged data from Remotely Piloted Aircraft System (RPAS), Real-time Kitematic (RTK), and CEE ECHO survey	Variable (1-20m)	NAD83 CSRS 2002	CGVD1928
Bathymetric LiDAR (CHS)	2015-2019	Plane-based bathymetric LiDAR	1m	NAD83	Chart Datum (LLWLT)
Custom Data (CHS)	2021	Bathymetric and Topographic Survey	1-20m	WGS 1984	Chart Datum (LLWLT)
Topographic LiDAR (GeoBC)	2017	Bathymetric LiDAR	1m	NAD83	CGVD2013
Topographic LiDAR (FLNRORD)	2015	Topographic LiDAR	1m	NAD83	CGVD2013
Canadian Hydrographic Service Non-Navigational (NONNA-10) Bathymetric Data (comprised of many data sources in the CHS catalogue)	2018 - 10 - 01	Bathymetric Surface	10m	WGS 1984	Chart Datum (LLWLT) for most but no official unified vertical datum
Canada West Coast Topo-Bathymetric	2021	Bathymetric Surface	10m	WGS 1984	Chart Datum (LLWLT)

DEM (DFO/NRCan)					
Canadian Digital Elevation Model (NRCan)	2011	Bathymetric and Topographic Surface	10m	WGS 1984	Chart Datum (LLWLT)
Bathymetric DEM of British Columbia, Canada (NOAA)	1930 - 2012	Bathymetric Surface	3 arc-second (~93m)	WGS 1984	Mean Sea Level (MSL)
Bathymetric DEM of Southeast Alaska, USA (NOAA)	2010	Bathymetric and Topographic Surface	Variable, ~16m-240 m	WGS 1984	Mean Higher High Water (MHHW)
Simulated Points (ONC)	2022	Bathymetric Points	1-2m	WGS 1984	CGVD2013
High Water Line for British Columbia (CHS)	2013	Coastline Shapefile	N/A	NAD83	N/A

4.0 DEM Processing and Development

Each data source went through a variety of processes to convert the horizontal and vertical datums, coordinate systems, data format, and spatial resolutions, in order to incorporate them into the DEMs and meet the specifications in Tables 1 and 2. Processing of the data and DEM surfaces was accomplished on Linux machines using a number of tools and scripts.

Software, scripts, and programs used:

- Generic Mapping Tools (GMT)
- LAStools
- MB-System
- Geospatial Data Abstraction Library (GDAL)
- Bathymetry smoothing python script
- ArcGIS Pro
- Global Mapper

This section is a summary of the processes to prepare each data source listed in Table 2 for integration into the DEM surfaces. All input data was required to be in XYZ format, meaning that each dataline had a longitude, a latitude, and an elevation value.

4.1 Data Conversion

Field Data (drone, GPS, and echosounder survey at Juskatla)

Geospatial data acquisition was completed by NHC at Juskatla. Combined data (including drone, GPS, and Cee Echo dual frequency echosounder data) was delivered in one XYZ .csv with variable resolution. To process this data prior to retrieval by ONC, octree filtering was used to reduce points and vegetation, and vegetation and floating points were removed manually.

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in Decimal Degrees
- Projection: UTM Zone 8 North
- Vertical Datum: CGVD1928
- Vertical Units: Metres

The data was then processed into the format required for DEM integration.

1. Converted the horizontal datum from NAD83 UTM Zone 8N to WGS-1984 in decimal degrees, and in XYZ format, using the cs2cs tool from MyGeodata Cloud (GeoCzech Inc, 2021).
2. Converted the vertical datum from CGVD1928 to CGVD2013 using Natural Resources Canada (NRCan) GPS-H (Government of Canada, 2022).
3. Generated .inf files for the XYZ files.
4. Created a datalist for the processed files.

Bathymetric LiDAR from CHS

This LiDAR was captured by plane using a Leica HawkEye 4x topo-bathymetric system. It uses an elliptical scan pattern for data collection. It was collected at a minimum height of 400m above the ground with a minimum of 20% sidelap on adjacent flight lines.

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in Decimal Degrees
- Projection: UTM Zone 9 North
- Vertical Datum: CGVD2013
- Vertical Units: Metres

The points classified as bare earth (ground only, vegetation and buildings removed) were removed by ONC and then the bathymetric data converted to XYZ for integration into the DEM. However, some additional processing was necessary to remove some erroneously classified bare earth points over water features before the datasets underwent processing for the DEM integration. This step was accomplished by viewing the LiDAR points in ArcGIS and deleting swaths of erroneous points that remained over known deep water areas.

1. Converted LAZ files to LAS using las2las from LAStools.
2. Converted the horizontal datum from NAD83 UTM Zone 9N to WGS-1984 in decimal degrees, and in XYZ format, using the cs2cs tool from MyGeodata Cloud.
3. Classify bare earth using “Classify LAS Ground” tool in ArcGIS Pro
4. Generated .inf files for each of the 1154 XYZ files.
5. Created datalist for the processed LiDAR dataset.

Additional processing:
It was noticed that several CHS LiDAR files contained docks, bridges, and other floating structures. Leaving these structures in the DEM would affect tsunami wave propagation, so therefore needed to be removed. These points were removed by manual selection in ArcGIS Pro.

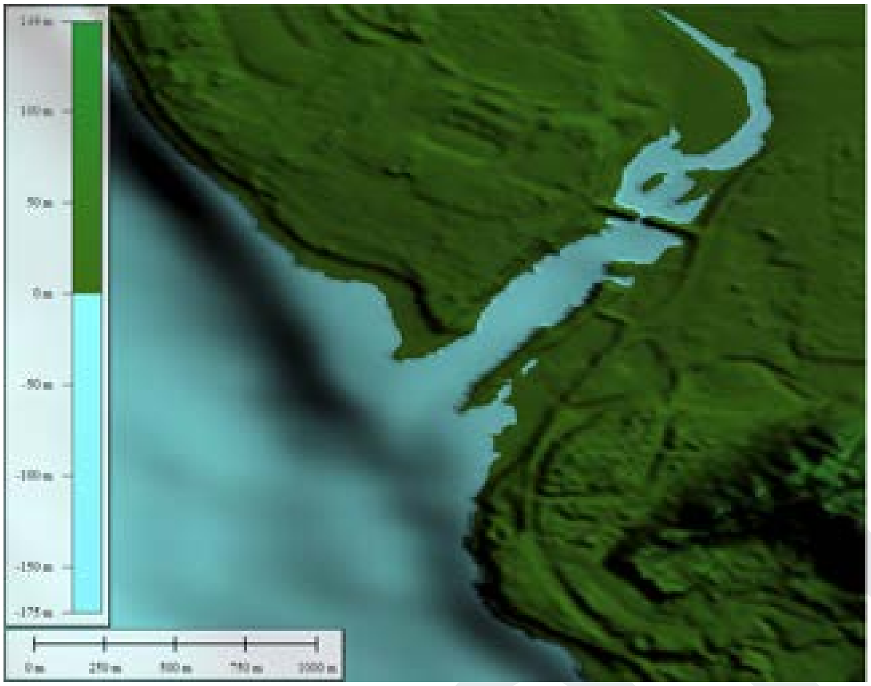

Figure 2. Comparison of the 10m Masset DEM before and after removal of docks present in CHS LiDAR. The top image is before point removal. The bottom image is after point removal.

Custom Data from CHS

Through a data agreement with CHS, multibeam, singlebeam and LiDAR data was compiled and obtained. The data was delivered in .CSAR format in two files, one for northern Graham Island surfaces (i.e. Masset Inlet and Port Clements), one for eastern Graham Island surfaces (i.e. Tlell and Daajing Giids). Only bathymetric values below 0m were retained for DEM creation since the LiDAR portions of the compilation dataset were found to not be generated from bare earth values, thus representing undesirable vegetation heights.

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates, Latitude and Longitude in Decimal Degrees
- Projection: GCS_WGS_1984
- Vertical Datum: Chart Datum (LLWLT)
- Vertical Units: Metres

The data was processed and converted into the format required for the DEM.

1. CARIS Easy View software was used to read the .CSAR format and export the multibeam surfaces as a text file, tab-delimited, with the data in geographic coordinates in decimal degrees
2. Converted the data to XYZ format

3. Converted the vertical datum from chart datum to CGVD2013 using a conversion grid provided by CHS
4. Clipped data to obtain only values less than 0m
5. Generated .inf files for each XYZ file
6. Created a datalist for the processed CHS multibeam dataset

Topographic LiDAR from GeoBC

GeoBC Topographic LiDAR is publicly available and was obtained from the GeoBC portal[1]. Data was obtained as 221 .laz files and covers northeast Graham Island (see Figure 11). Significant metadata records do not exist. As such, assumptions needed to be made regarding the vertical datum of the dataset. Additionally, as this dataset did not undergo significant QA/QC by GeoBC, so some files required manual removal of points.

Linux tools and scripts were used to process the GeoBC .laz files into a format suitable for DEM integration.

1. Converted LAZ files to LAS using las2las from LAStools
2. Converted the horizontal datum from NAD83 UTM Zone 9N to WGS-1984 in decimal degrees, and in XYZ format, using a cs2cs tool
3. Generated .inf files for each of the 221 XYZ files
4. Created datalist for the processed GeoBC LiDAR files

Additional Processing:
There were a number of erroneous points that needed to be removed as they contained points above 0m in overwater areas that are known to be deep. This step was accomplished by viewing the LiDAR points in ArcGIS Pro and deleting erroneous points that remained over water areas.

[1]https://governmentofbc.maps.arcgis.com/apps/MapSeries/index.html?appid=d06b37979b0c4709b7fcf2a1ed458e03

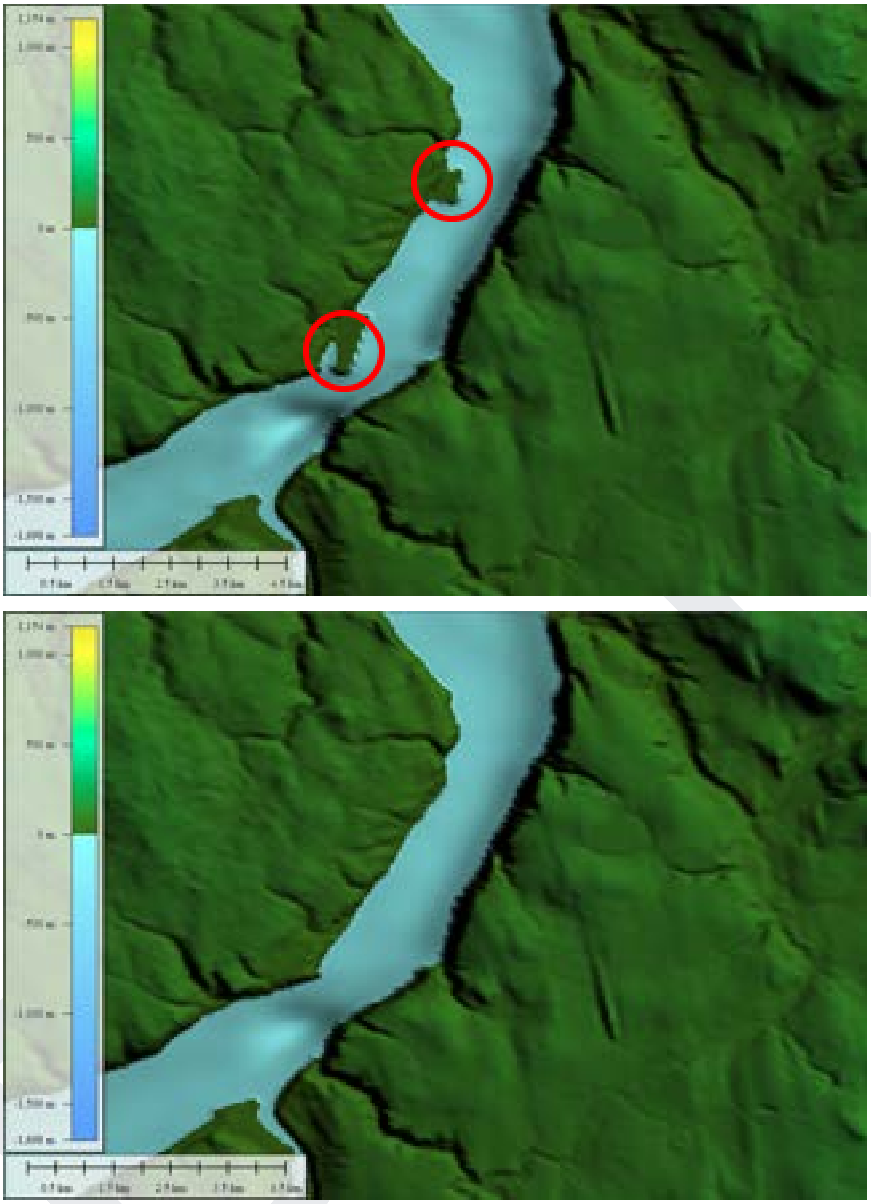

Figure 3. Comparison of the Regional 40m DEM before and after removal of erroneous GeoBC LiDAR points. The top image is before alteration. The bottom image is after alteration.

Topographic LiDAR from FLNRORD

Topographic LiDAR from FLNRORD was obtained from NHC. Unfortunately, no metadata existed for this dataset, so it was assumed the vertical and horizontal datums were consistent with GeoBC data as there were consistencies between the data formats. It is likely that this data was collected in 2015 based on information obtained from the lasinfo tool from LASTools, but without metadata, it was not possible to confirm this assumption.

Linux tools and scripts were used to process the GeoBC .las files into a format suitable for DEM integration.

1. Use lasinfo tool from LASTools to obtain details about these files
2. Converted the horizontal datum from BC Albers to WGS-1984 in decimal degrees, and in XYZ format, using the cs2cs tool from LAStools
3. Generated .inf files for each of the 31 XYZ files
4. Created datalist for the processed GeoBC LiDAR files

Non-Navigational (NONNA-10) Bathymetric Data from CHS

CHS has publicly available Non-navigational (NONNA) bathymetric data available from their data portal in both 10m and 100m horizontal resolution (https://data.chs-shc.ca/map). The NONNA-10 (10m resolution) for the AOI (area of interest) was downloaded from the CHS data portal in ASCII text format.

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates, Latitude and Longitude in Degrees, Minutes, Seconds
- Projection: GCS_WGS_1984
- Vertical Datum: Chart Datum (LLWLT)
- Vertical Units: Metres

The data was processed and converted into the format required for the DEM.

1. Converted geographic coordinates to Decimal Degrees, rearranged from YXZ to XYZ, and removed extraneous characters from datalines using a custom python script built in-house
    a. Example line of the original data: 49-00-00.712N 126-02-57.407W 60.09020
    b. Example line of the converted data: -126.079182778 49.0997838889 60.09020
2. Converted the data to XYZ text format from ASCII .txt
3. Converted the vertical datum from chart datum to CGVD2013 using a conversion grid provided by CHS
4. Split the converted XYZ files into more manageable data chunks using the GMT block median tool
    a. This resulted in 449 XYZ files, tab delimited
5. Generated .inf files for each XYZ file
6. Created a datalist for the processed CHS NONNA-10 dataset

Canada West Coast Topo-Bathymetric DEM from DFO/NRCan

A joint partnership with Fisheries and Oceans Canada (DFO) and NRCan resulted in a derived DEM with the best data available from multiple sources with a horizontal resolution of 10m. This data is publicly available through the Government of Canada[2]. Data was obtained in geodatabase raster format, and was used as a background dataset to fill data gaps between the more reliable and higher resolution datasets. Only the bathymetric data (below 0m) was used in DEM generation due to influence from vegetation heights discovered in the topographic values.

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates
- Projection: GCS_WGS_1984
- Vertical Datum: Chart Datum (LLWLT)
- Vertical Units: Metres

The data was processed and converted into the format required for the DEM.

1. Converted the GDB raster into .tif in WGS84 using ArcGIS Pro
2. Ran tif2chunks2xyz script to convert .tif to XYZ
3. Converted grid from Chart Datum to cgvd2013 using conversion grid provided by CHS
4. Split the converted XYZ files into more manageable data chunks using the linux split command
    a. This resulted in 46 XYZ files, tab delimited
5. Clipped data to obtain only values less than 0m
6. Generated .inf files for each XYZ file
7. Created a datalist for the processed west coast DEM dataset

Canadian Digital Elevation Model from NRCan

Data was downloaded via FTP in GeoTIFF format, courtesy of the Government of Canada - Natural Resources Canada[3]. This data acquisition resulted in 11 GeoTIFFs (the number of CADEM grids that intersected the AOI) with a grid resolution of 0.00020833333 degrees (approximately 20 Metres).

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in Decimal Degrees
- Projection: GCS_North_American_1983_CSRS
- Vertical Datum: CGVD28
- Vertical Units: Metres

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[2] https://open.canada.ca/data/en/dataset/e6e11b99-f0cc-44f7-f5eb-3b995fb1637e
[3] Ftp.geogratis.gc.ca/pub/nrcan_rncan/elevation/cdem_mnec

Linux tools and scripts were used to process the CADEM into elevation subsets and convert datums.

1. Removed a standard no data value of -32767 from all files
2. Split the 11 GeoTiffs into subsets called ‘chunks’, 500 row by 500 column data files, and then to XYZ files, using a tif2chunks2xyz script from GDAL
    a. This resulted in 1101 text file format XYZ files, tab delimited, which were organized into 11 folders, one for each of the original GeoTIFFs
    b. It was decided that the vertical and horizontal datums did not need to be converted to WGS-1984 and CGVD2013, as the difference would be negligible at the desired DEM surface resolution (Natural Resources Canada, 2020)
3. Generated .inf files for each XYZ file in every subset folder
4. Created a datalist for each of the subset folders for a total of 9 datalists
    a. 103P
    b. 103O
    c. 103K (later reprocessed, see note below)
    d. 103J (later reprocessed, see note below)
    e. 103I
    f. 103H
    g. 103G (later reprocessed, see note below)
    h. 103F (later reprocessed, see note below)
    i. 103C
    j. 103B
    k. 103A

Additional processing:
It was noticed in preliminary test DEM surfaces that there was some issue in higher resolution surfaces (2m) in the overlapping areas between the CADEM and the available LiDAR. To remedy this issue, the CADEM subsets that overlapped with the LiDAR in key areas of the AOI, 103K, 103J, 103G, 103F were clipped to remove any overlap with the LiDAR. The newly clipped subsets and the corresponding datalists were used to replace the originals listed above. The replacements were:

l. ClippedtoLidar/103K (later reprocessed an additional time, see note below)
m. ClippedtoLidar/103J
n. ClippedtoLidar/103G
o. ClippedtoLidar/103F

Within the Juskatla area, 103K was lowered 3m. This was completed because there were deviations of an average of 3m observed between the higher resolution NHC survey and the lower resolution NRCan data at Juskatla. When the 103K file was lowered 3m, it was found to be significantly more consistent with the NHC Juskatla survey. This was accomplished by drawing a polygon surrounding the Juskatla area, selecting all points within the polygon and subtracting 3m (see Figure 4). It was decided not to lower the CADEM in other areas as there was not high-resolution field data available to determine whether this was needed.

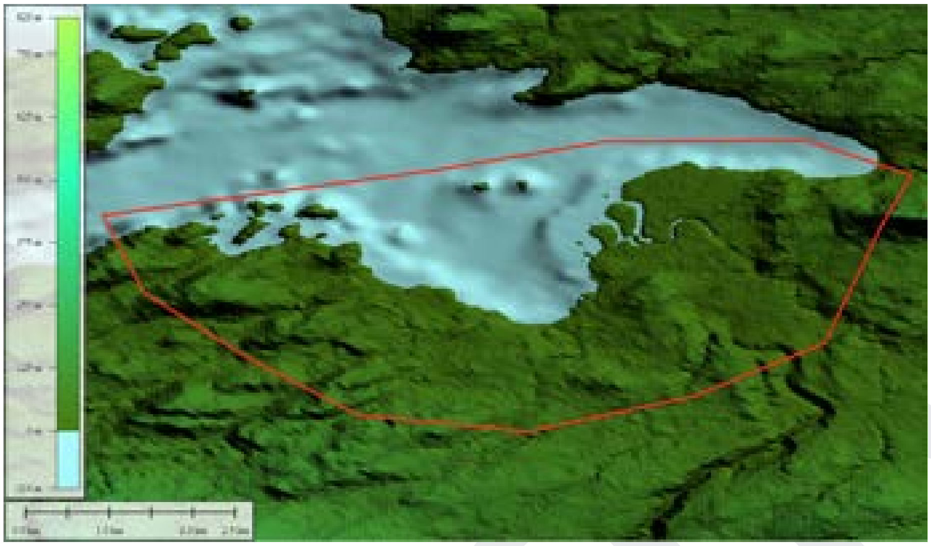


Figure 4. Polygon representing the area in which CADEM was lowered by 3m in the Juskatla area to ensure consistency with NHC Juskatla survey.

Bathymetric DEM of British Columbia, Canada from NOAA

Bathymetric data at 3 arc-second resolution (approximately 90m) was obtained as a netCDF from the National Geophysical Data Center[4], courtesy of NOAA. This dataset was used to fill in the data gaps between the higher resolution bathymetric data in the lower resolution DEM grids.

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates, Latitude and Longitude in Decimal Degrees
- Projection: GCS_WGS_1984
- Vertical Datum: MSL
- Vertical Units: Metres

Linux tools and scripts were used to process the NOAA netCDF into a format suitable for DEM integration.

1. Converted to GeoTIFF format using the grdconvert tool from GMT
    a. It was decided not to convert the MSL to CGVD2013 since the original data resolution of ~90m is a very coarse value and would have negligible impact on the final DEM. The difference between the two datums is 1-3 metres.

[4] https://catalog.data.gov/dataset/british-columbia-3-arc-second-bathymetric-digital-elevation-model

2. Clipped the GeoTIFF to the coarsest extents of the AOI, -134.6/-127.7/54.2/51.6
3. Split and convert the clipped GeoTIFF into 'chunks', 500 row by 500 column data files, and then to XYZ files using GDAL tool tif2chunks2xyz
4. Generated .inf files for each XYZ file
5. Created a datalist for the processed NOAA dataset

Additional processing:
It was noticed in preliminary test DEM surfaces that there was some issue with the coarse resolution of the NOAA, ~90m, data in resolving the elevation in the narrow coastal inlets. The inlets, some as narrow as 300m, resulted in few data points from the NOAA dataset (3-4 in the narrowest areas) with values that were vastly different from reality, as evidenced by the higher resolution multibeam and singlebeam bathymetric values in the same areas. This was likely due to the averaging of elevation values for each datapoint in the coarse NOAA dataset, which would be averaged from a large range of values due to the steep nature and sudden elevation changes over small horizontal distances in these coastal inlets. Since these values weren't reliably representing the inlets, the NOAA dataset was clipped so that only the open ocean and other wider coastal areas were preserved. This clipped dataset then underwent steps 4-5 above and this was the data used for integration into the lower resolution DEM surfaces.

Bathymetric DEM of Southeast Alaska, USA from NOAA

Bathymetric and Topographic DEM was generated by the National Geophysical Data Center (NGDC), an office of NOAA. These DEMs were generated from various datasets in the region. It is publicly available from the National Geophysical Data Center[5], courtesy of NOAA, and obtained as a NetCDF. This dataset was used to fill in the bathymetric data gaps outside of Canadian waters.

Linux tools and scripts were used to process the NOAA netCDF into a format suitable for DEM integration.

1. Converted to GeoTIFF format using the grdconvert tool from GMT
    a. It was decided not to convert the MHHW to CGVD2013 since the original data resolution can be up to 240m, it was considered too coarse for a conversion to be necessary as it would have negligible impact on the final DEM.
2. Clipped the GeoTIFF to include just what is relevant to the AOI, -134.6/-129.2/55.8/54.2
3. Converted GeoTIFF to XYZ using the cs2cs tool from LAStools
4. Generated .inf files for each XYZ file
5. Created a datalist for the processed NOAA dataset

[5] https://catalog.data.gov/dataset/juneau-alaska-coastal-digital-elevation-model

Simulated Points from ONC

Sangan River and Chown Brook

Simulated points were created at Sangan River and Chown Brook. This was done to ensure the river was more representative of reality. Without the manual creation of points, the river does not properly appear in the 10m DEM, which would affect water propagation during the modelling phase. To do this, points were created throughout the river channel and assigned an elevation value of -0.3m. ArcGIS Pro was used to create manual points for Sangan River and Chown Brook to be integrated into the 10m Masset DEM.

1. Created a polygon extending across Sangan River and Chown Brook
2. Used “Create Random Points” tool in ArcGIS Pro
3. Added XY coordinates to the points and a elevation value of -0.3m (an assumed average value for the Sangan River and Chown Brook elevation)
4. Exported as .txt and then converted to XYZ
5. Created datalist for the simulated Sangan River and Chown Brook points

Figure 5. Polygon representing location in which the simulated points were created within Sangan River and Chown Brook River.

Tlell River

Simulated points were created at Tlell River as similar issues were noted as in Sangan River and Chown Brook. Without the manual creation of points, Tlell River was not representative of reality and appeared 5m above sea level, inhibiting potential inundation up river. To remedy this, points at 0m and 0.5m elevation values were created along the river bed using ArcGIS Pro, using the same method as Sangan River and Chown Brook described above, which were then integrated into the Tlell 10m DEM. 0m elevation values were assigned at the mouth of the river, and then transitioned to 0.5m upriver (with respect to CGVD2013).

1. Created a polygon extending along Tlell River
2. Used the “Create Random Points” tool in ArcGIS Pro
3. Added XY coordinates to the points and elevation values of 0m and 0.5m (assumed values for the Tlell River elevation)
4. Exported as .txt and then converted to XYZ
5. Created datalist for the simulated Tlell River points

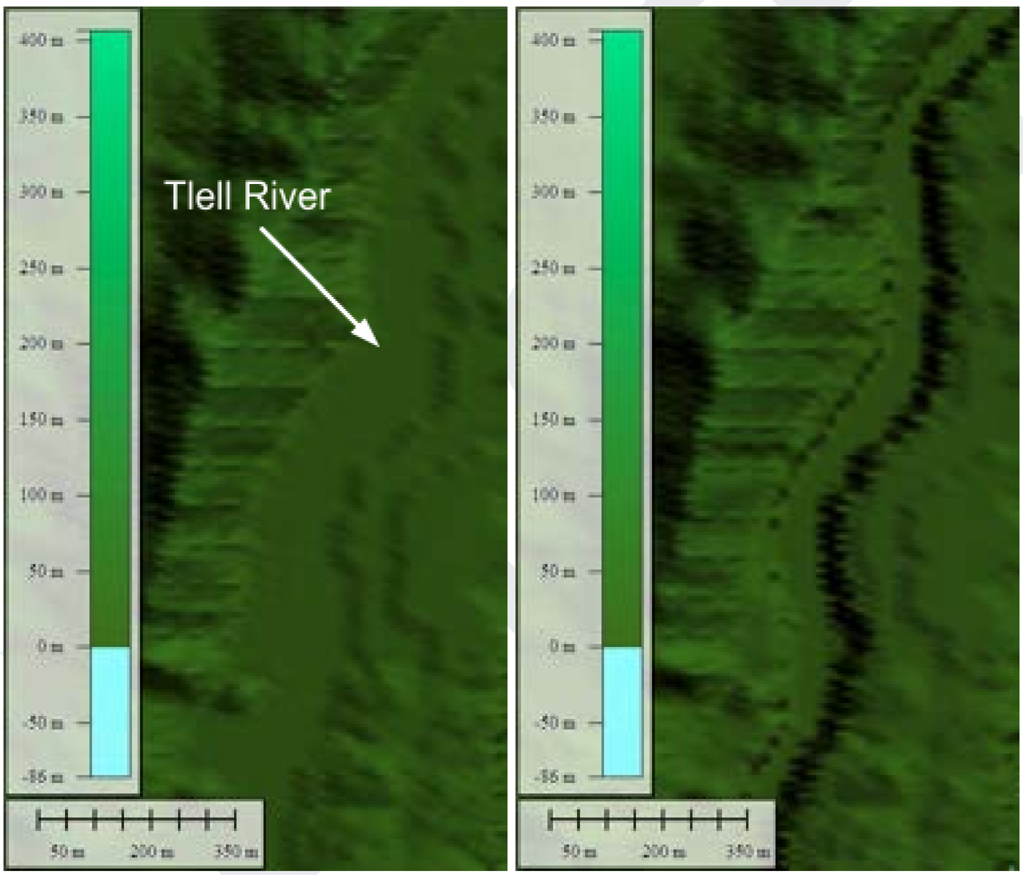


Figure 6. Comparison of the Tlell 10m DEM before and after simulated river points. The image on the left is before simulated river points were created. The image on the right is after simulated river points were created. Note that issues with river representation were not seen where higher resolution data was available (southernmost portion of Figure 6).

Juskatla Inlet

Simulated points were created at Juskatla inlet to supplement the NHC Juskatla survey, which were limited to the developed segment of the shoreline. Due to the sparse nature of the collected points and the distance between the swaths in the NHC Juskatla survey, artificially shallow elevations were modelled during the DEM generation. To rectify this, 9 polygons were drawn encompassing the area causing artificial mounds, and points were created within each polygon. The value of the points was based on the average value of the Juskatla survey within each polygon (see Figure 7).

Figure 7. Simulated points encompassing Juskatla survey points (dark blue). Each polygon colour represents a different elevation value. Elevation values were calculated based on average elevation of Juskatla survey points within the polygon.

ArcGIS Pro was used to create simulated points for the Juskatla Inlet to supplement the NHC survey.

1. Created 9 polygons extending across the impacted area in the Juskatla 10m DEM
2. Used the “Create Random Points” tool in ArcGIS Pro for each polygon
3. Added XY coordinates to the points and a elevation value based on the surrounding average of the NHC survey
4. Exported as .txt and then convert to XYZ
5. Created datalist for the simulated Juskatla Inlet points

High Water Line for British Columbia from CHS

No processing was necessary for this dataset.

4.2 DEM Surface Processing

Before the DEMs were created, all the data needed to be prepped into XYZ files with accompanying .inf files for each as well as a datalist for each dataset. The .inf file provides an overview of the XYZ files and is a necessary input for the MB Grid program. The .inf contains the amount of points, the dataset extent, and the maximum/minimum values. The datalist is a text file that contains the file names for each of the XYZ files. There is a unique datalist for each input dataset folder that contains XYZ and .inf files.

Once all of the unique datalists were generated, one master datalist was created so that each of the unique datalists can be referenced and given a proper weight. In the master datalist, individual datasets can be commented out, which means that when the DEM grid is generated, these datasets won't be used. This is a useful function to have in order to test DEM creation and was used to evaluate individual dataset contributions to the final integrated DEM grids.

There were 16 datasets in the master datalist for this project. With MB Grid, the weights of each dataset in the master datalist determine which dataset gets the highest priority when determining the value of each point in the DEM surface. Therefore, the higher resolution and the most reliable datasets were assigned the highest weights for this project. Table 4 below lists the datasets in the master datalist and the weights assigned to each for this project.

Table 4. Dataset weights in Master Datalist	
Dataset Name	**Weight**
Field data (GPS, drone, and bathymetric survey at Juskatla)	50
Topographic LiDAR (GeoBC)	50
Topographic LiDAR (FLNRORD)	25
Bathymetric LiDAR (CHS)	20
Custom Data (CHS)	20
Non-Navigational (NONNA-10) Bathymetric Data (CHS)	15
Canada West Coast Topo-Bathymetric DEM (DFO/NRCan)	1
Canadian Digital Elevation Model (NRCan)	1
Bathymetric DEM of British Columbia, Canada (NOAA)	1
Bathymetric DEM of Southeast Alaska, USA (NOAA)	1

Simulated Points (ONC)	Variable - always given priority over underlying points.

An MB Grid function was used to integrate all of the above processed and weighted datasets into the final DEMs. For each DEM grid, the extents and resolution were specified when running the tool and the dataset weights remained the same for each grid.

The MB Grid program is used to grid bathymetry in the hydrography industry and it is part of the MB System program, an open source seafloor mapping system developed by the Monterey Bay Aquarium Research Institute. MB Grid uses a thin plate spline interpolation to create a grid using a gaussian weighted average. Users can specify the grid extent and resolution, as well as other parameters. The program outputs a netCDF GRD file, which can then be converted to a more user-friendly GeoTIFF format using the GDAL tools. To create the grid, the same interpolation methods were used for both topographic and bathymetric data.

Due to the sparse nature of the bathymetry data throughout much of the remote coastal areas within the grids, some of the bathymetric areas of the DEMs contained visible artifacts as a result of stitching together the various data sources, particularly those of differing resolutions. Therefore, the GeoTIFF DEM models were smoothed using a python script that was provided by modellers at NOAA. This script implements a user-specified smoothing factor to smooth only the bathymetric values of the DEM surface (values below 0m). In the case of the Masset grid, where many artifacts were visible, a smooth factor of 30 was used. However, smoothing factors of only 20 and 10 were used for the Daajing Giids and Tlell grids, respectively, due to fewer visible artifacts.

5.0 Quality Checks, DEM Usage & Limitations

5.1 Quality Checks

In order to evaluate and check results of the DEM models, a number of visual checks were performed. The software programs ArcGIS Pro and Global Mapper were used for most of these checks. For the first checks, Global Mapper was used to visualize the DEMs with hillshades and colour shading to determine the elevation changes, and compare these with satellite imagery of the area to determine if the model was a reasonable representation of reality (Figure 6). These comparisons aided in finding some of the initial issues that led to the above mentioned reprocessing of some of the input datasets.

Next, the DEM models were compared with the CHS navigational charts. CHS charts were used to examine the elevation of the seafloor in the DEMs to ensure that the models produced reliable and realistic results, especially in the narrow inlets and along the coastline. Elevation contours at the -2, -5 and -10 metre intervals were used to confirm elevation in the DEM and ensure that the model was a reasonable representation of reality.

Following the elevation comparisons between the charts and the DEM models, satellite imagery was used to compare the coastlines between the models and reality. The remotely sensed imagery was also used to determine whether small islands and coastal rocks modelled in the DEM were an accurate representation of reality by checking if these features were also visible in the imagery. The imagery checks ensured that islands in the DEMs are real, rather than artifacts in the DEMs. Additionally, this imagery allowed for confirmation of road placement in the DEM to ensure that these important infrastructure features were accounted for in the models. Furthermore, the imagery was used to evaluate the representation of key rivers in the models. This was an important step because the interaction of a tsunami with a river impacts the inundation modelling results, which is of particular concern near communities and infrastructure.

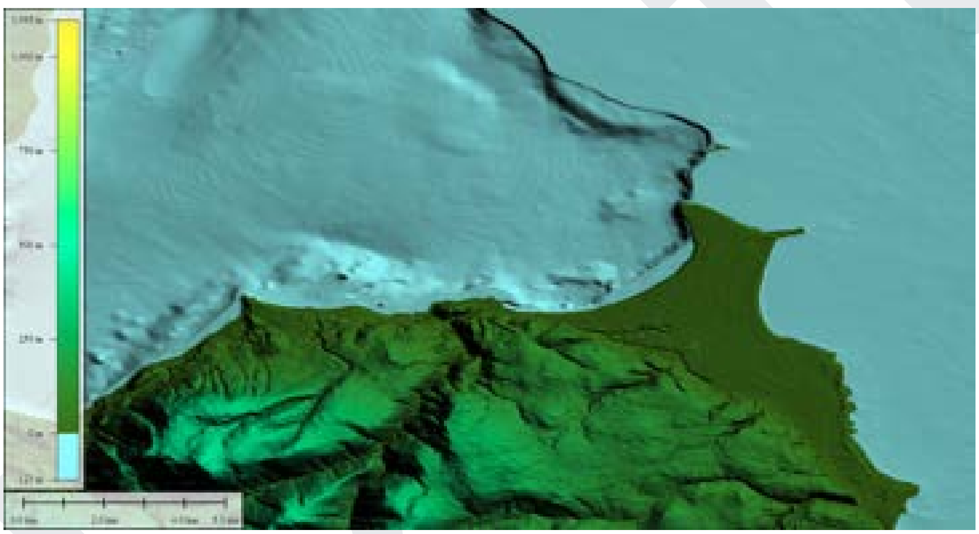


Figure 8. Image comparing Skidegate Inlet 10m DEM in the vicinity of Sandspit with satellite imagery in Global Mapper.

5.2 Dataset limitations

Due to the sparse coverage of high resolution data in some parts of the AOI, lower resolution datasets were used to fill the gaps where there was no high resolution data available. For example, NOAA's Bathymetric DEMs of British Columbia and Alaska, 90 metre resolution, were used to fill the gaps in the open ocean. However, due to the low resolution of this dataset, it was excluded from the inland coastal areas due to the narrow inlets and fjords being poorly represented at this resolution.

Similarly, to fill the sparse coverage over the land topography, the lower resolution Canadian Digital Elevation Model (CADEM) was used. Figure 9 shows the accuracy of the CADEM, as specified by NRCan, to be between 0-15m throughout most of the AOI. This product captured the elevation values relatively well in most of the AOI, but there were instances where the roads and coastline weren't accurately represented in the models. Fortunately, the high resolution CHS LiDAR dataset covered most of the AOI at the lower elevations, which are the most important, so the CADEM was only used to model higher elevations where the LiDAR wasn't captured.

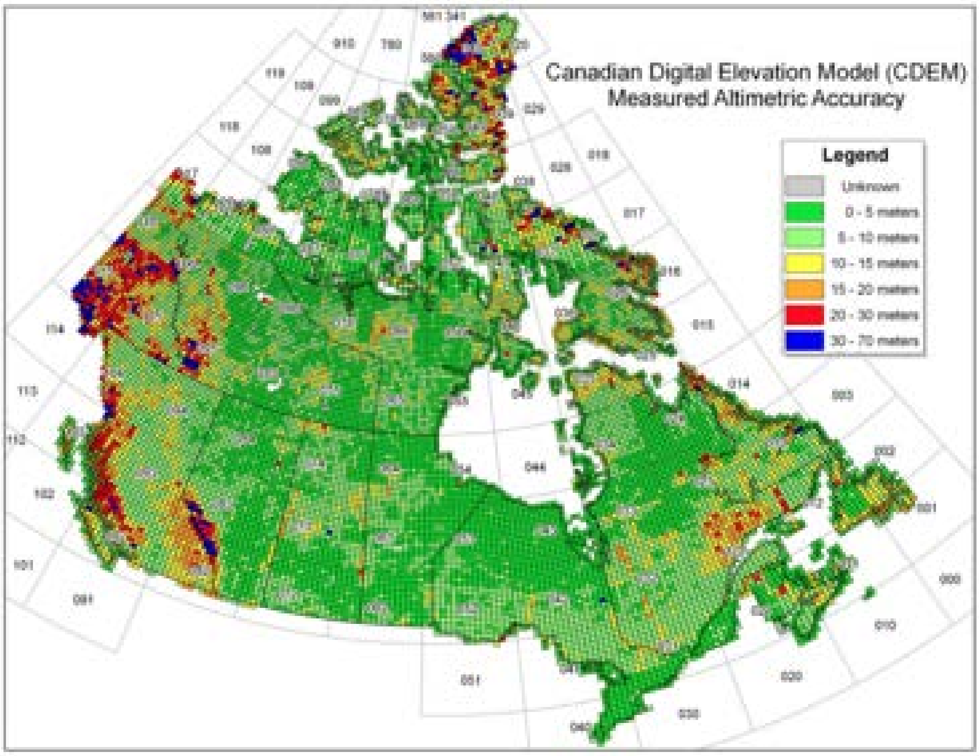


Figure 9. Natural Resources Canada map showing CADEM altimetric accuracy from the Canadian Digital Elevation Model Product Specifications report.

Additionally, it was found that due to lower resolution datasets in the Sangan River, Chown Brook and Tlell River areas, the rivers were not properly captured in the output DEM. In areas with lower resolution data, elevation values are averaged over larger areas, which can cause smaller features (such as rivers) to not be properly represented in the output DEM. To rectify this, simulated points were created at Sangan River, Chown Brook and Tlell River based on surrounding dataset points and examination of navigational charts and satellite imagery. However, with the manual creation of points, uncertainty is introduced as these values are estimations. Without additional field data to confirm estimated elevation values, caution should be exercised when planning for emergencies in areas where manual points were created and in inland areas adjacent to rivers and streams.

Modifications to GeoBC LiDAR and CHS data were also made based on examination of field data, as well as comparisons with navigational charts and satellite imagery. Though these modifications and deletion of erroneous points improved the output DEM, without further ground control points or field data, the accuracy of these modifications can’t be confirmed.

5.3 DEM Usage and Limitations

DEMs can be used for a variety of purposes. Slope maps, hillshades, and viewsheds created from DEMs can be useful for fire forecasting and emergency response planning, just as a small example of how DEMs can be used. However, the DEMs developed as part of this project were not reviewed for uses other than tsunami modelling. Caution should be taken when using these DEMs as they are models and are only a representation of reality, generated using multiple datasets that originated from numerous sources and were produced with significant interpolation due to the nature of the sparse high resolution data in some of these remote areas.

Both the topography and bathymetry in these DEMs is only as good as the input data, and some of the areas where the input data was knit together by the DEM grid algorithm, and areas of sparse data, show minor artifacts that may impact other uses of the DEMs. These grids can be used to get a good estimation of overall elevation, but CHS charts should be used to confirm elevation for navigation.

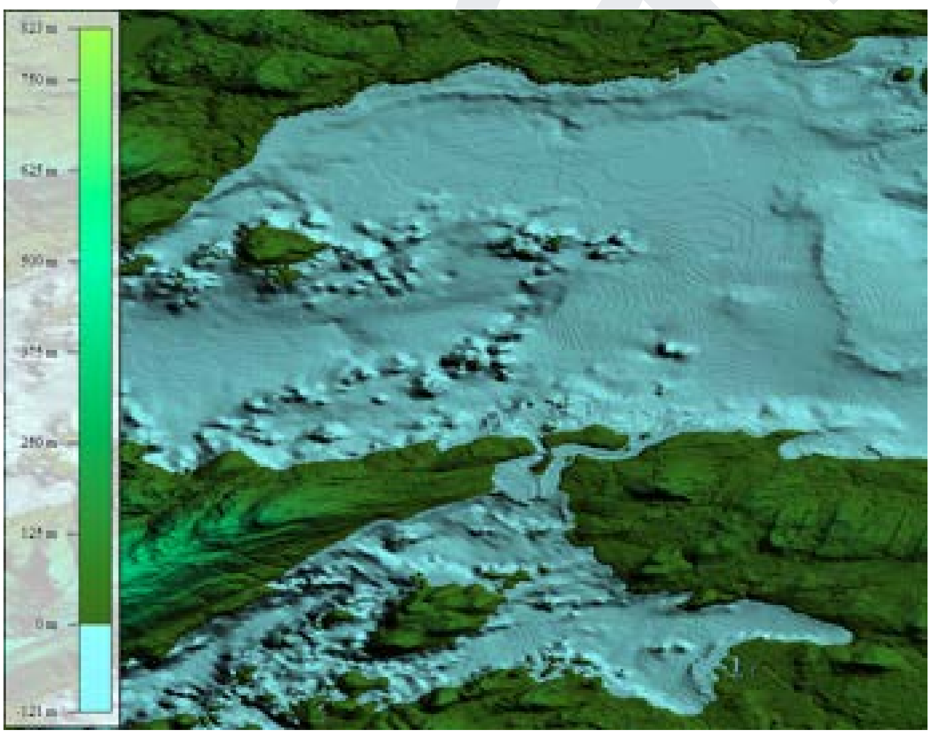
In addition, although the DEMs are modelled at 10m resolution, that does not mean that all the input datasets used were 10 metre resolution or better, and interpolation was necessary to generate a continuous surface with a grid spacing of 10m.

Intertidal zones are also inherently challenging to model due to the difficult nature of data collection in the transition zone between bathymetric and topographic data and the complexity of capturing these evolving coastal zones. While there was bathymetric LiDAR available through much of the study areas covering these zones, the data was not available for the entirety of the coasts. Port Clements and Juskatla are areas where the bathymetric LiDAR was not available and so the coastal transition zone is very approximate. Therefore, in areas where the intertidal zone was not covered with bathymetric LiDAR, the resulting DEMs may only be an approximation of reality.

Coastal rivers and estuaries are additional examples of areas that are difficult to model due to lack of data. Therefore, the elevations of rivers tend to be marginally represented and may only be approximations of reality. The bathymetric LiDAR obtained for this project improved some of these areas, but did not penetrate the water deep enough throughout to accurately reflect the waterbed elevation in its entirety. There are many factors that may influence the ability for bathymetric LiDAR to penetrate rivers with the presence of surface waves as one of the most impeding factors (Chi-Kuei Wang et. al., 2007).

Another limitation of the grids is the coordinate system conversions between datasets. The GeoBC and CHS LiDAR originally came in a UTM coordinate system and these coordinates had to be converted to WGS84 horizontal datum in decimal degrees for the modelling process. The difference between the original data and converted data is negligible with a horizontal difference of less than 1 centimetre. Also, while most of the data was converted to the CGVD2013 vertical datum, some datasets were left in their original datum due to it being a lower resolution dataset. It was decided that converting the datums of these poorer resolution datasets would have little to no influence on the DEMs and the results of tsunami modelling. For example, NOAA's Bathymetric DEM was originally in mean sea level and due to the poor resolution of this dataset it was not converted to CGVD2013 and instead left in its original datum.

Finally, an additional consideration to the use of these DEMs is the fact that the bathymetric parts of the model underwent a smoothing process. This process was necessary in order to smooth out any small pockets or abrupt artificial features that exist due to the sparse high resolution data and how the mb-grid algorithm interpolates between the various inputs. This smoothing operation is acceptable for tsunami modelling. However, it does smooth out some of the smaller features that exist on the seafloor, impacting the resolution of those features and potentially affecting other uses for the DEMs. However, without the smoothing, too many obvious artificial features would remain in the models, to the detriment of the tsunami modelling, which is the primary purpose for these DEMs. Figure 10 shows a comparison of the Port Clements 10m DEM before and after smoothing. It should be noted that the bathymetry, in blue, has had the rough features softened, but the land remains unaltered.



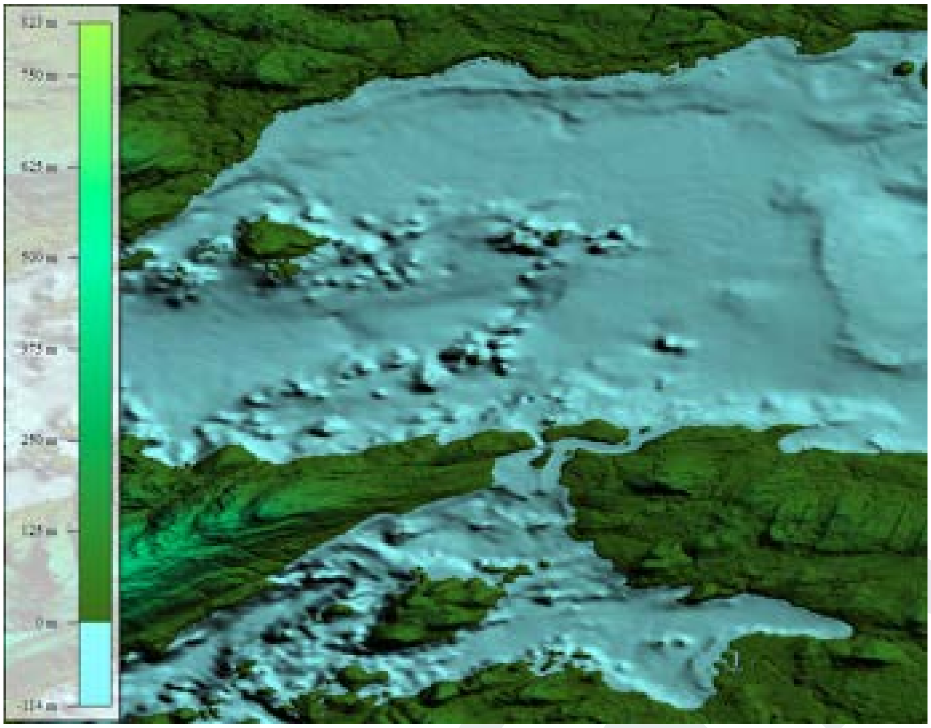


Figure 10. Comparison of the Port Clements 10m DEM before and after bathymetry smoothing. The top image shows the DEM before smoothing, and the bottom image shows the DEM after smoothing.

Due to the above mentioned factors, these models should not be used for navigation purposes, or other uses requiring high accuracy, especially those requiring accuracy of greater than 10m. Proceed with caution and take into account these limitations when sharing and using these models.

6.0 References

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Annex A: Maps of Data Extents

This section contains the maps of the extents for the high resolution datasets used for this project. The coverage of each dataset is shown with the extents of the final 10m DEM grids overlaid on top.

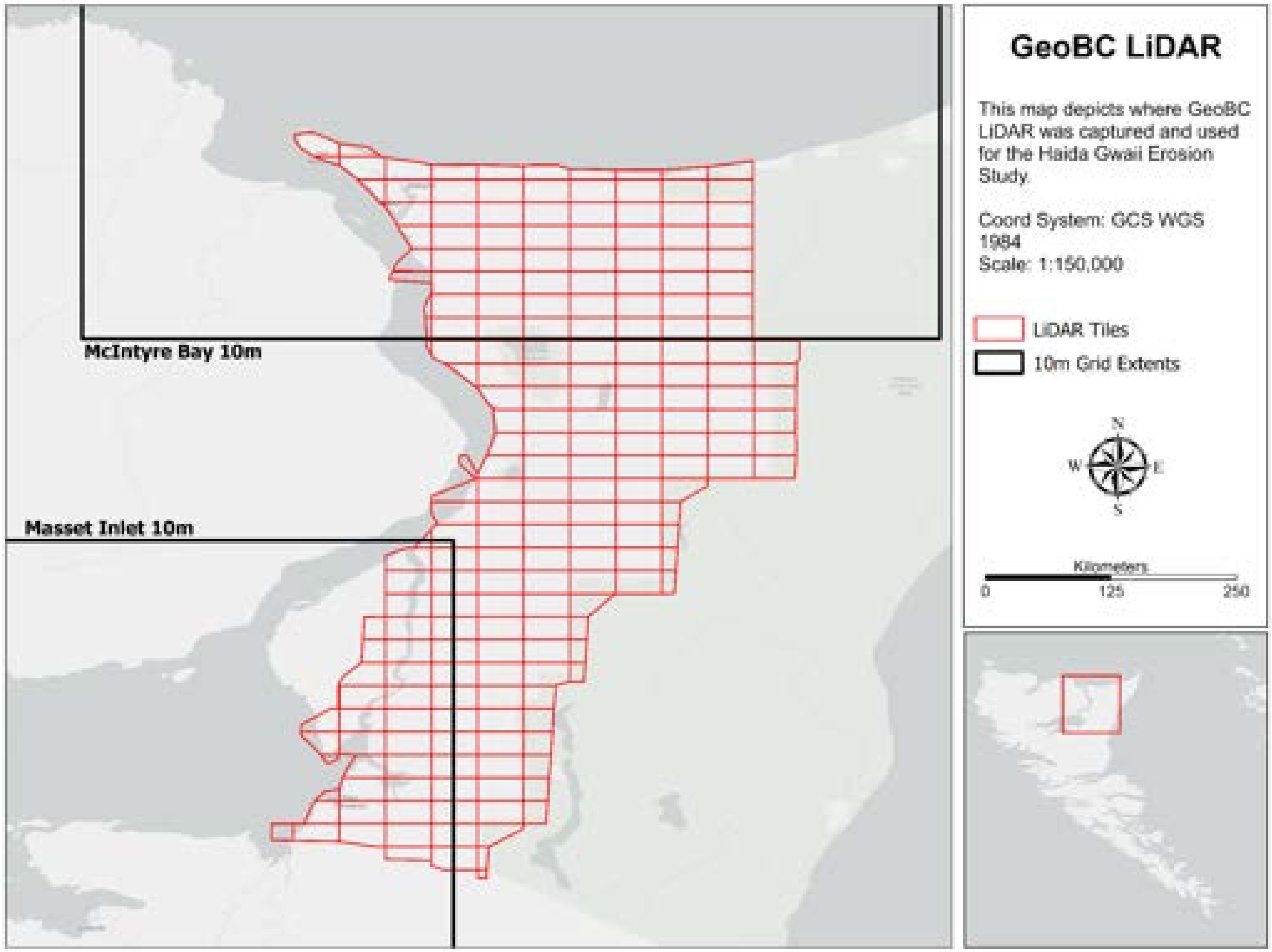

Figure 11. Map of GeoBC LiDAR extent

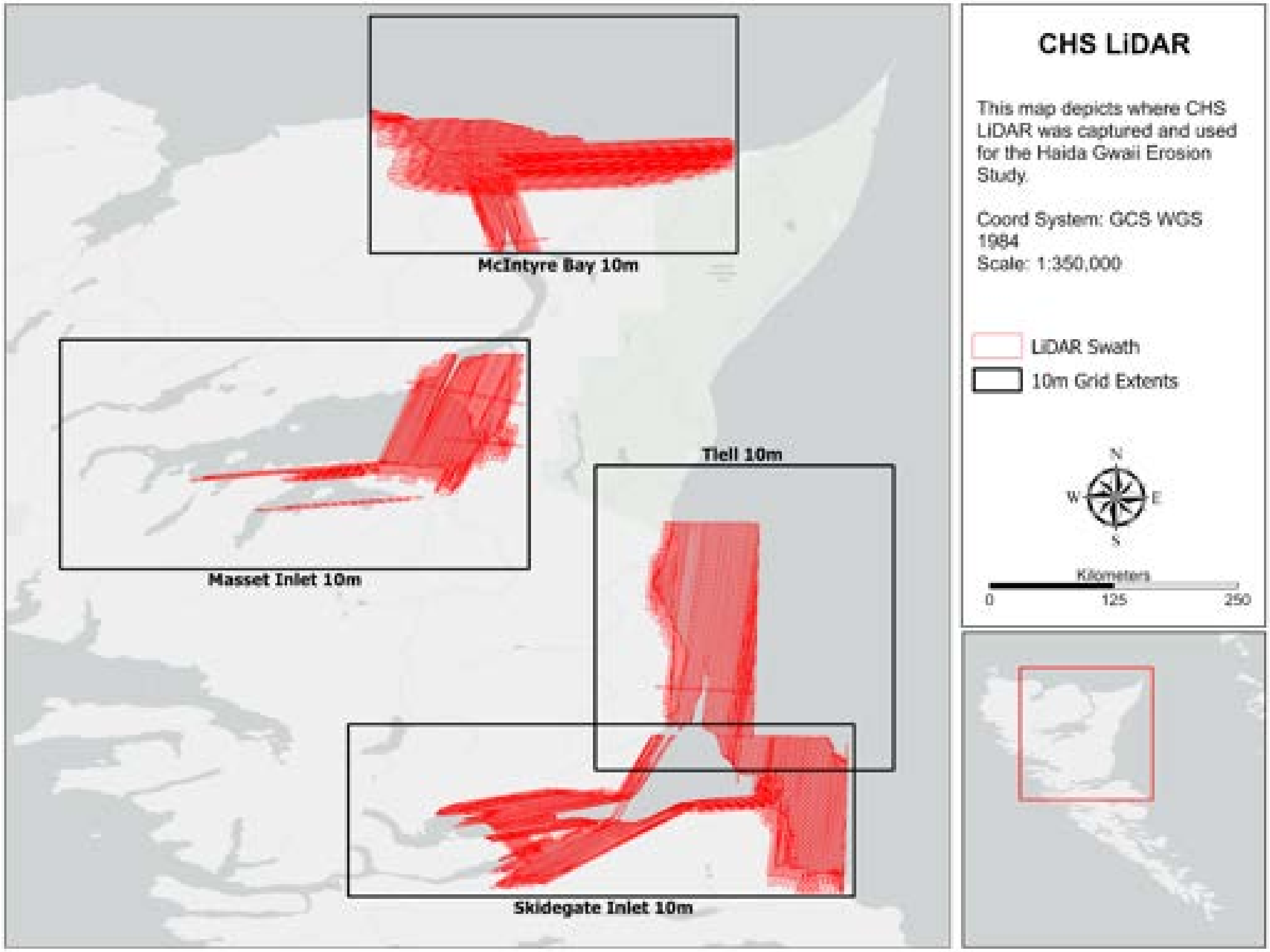

Figure 12. Map of CHS Bathymetric LiDAR extent

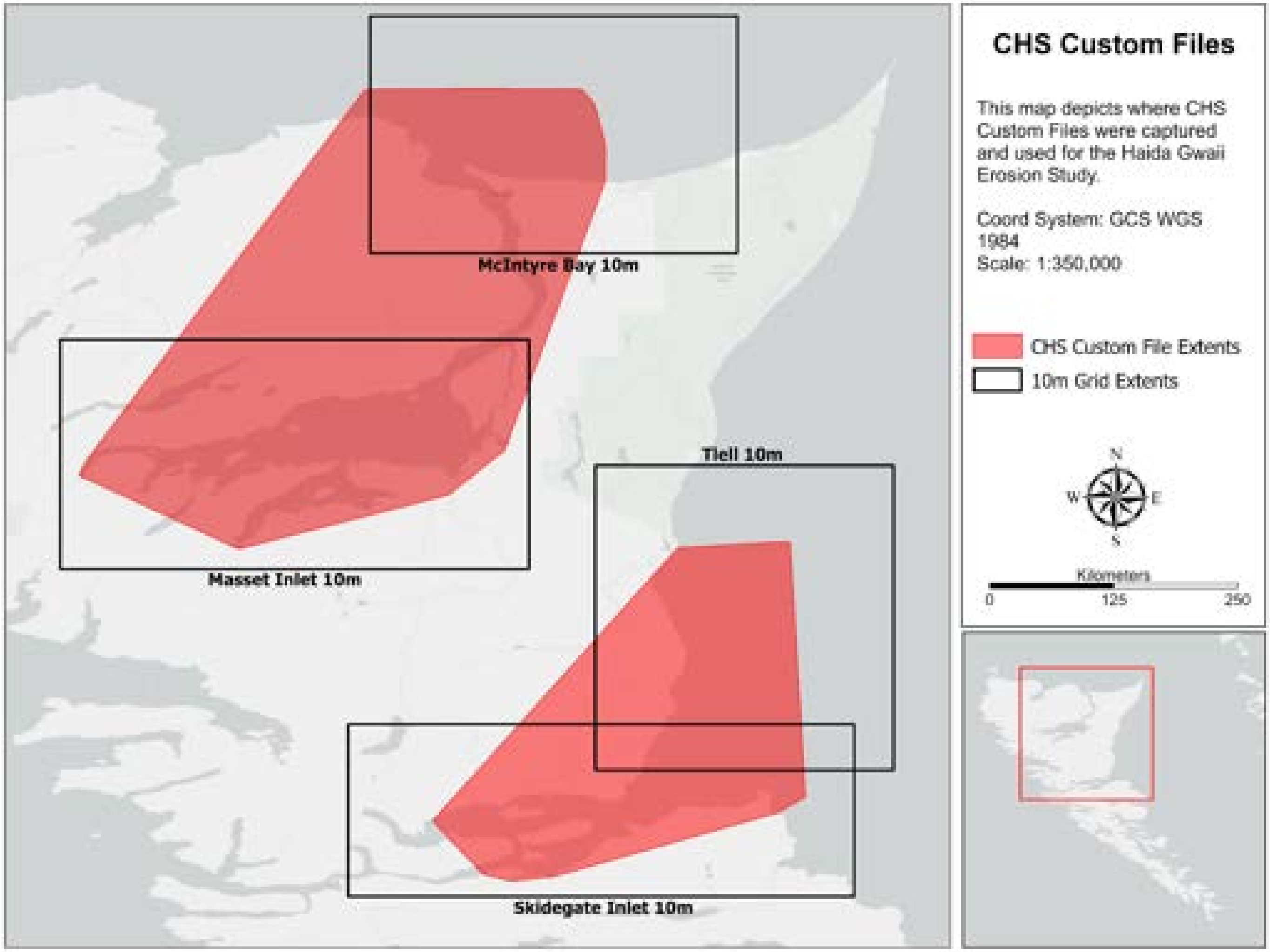

Figure 13. Map of CHS Custom Files extent

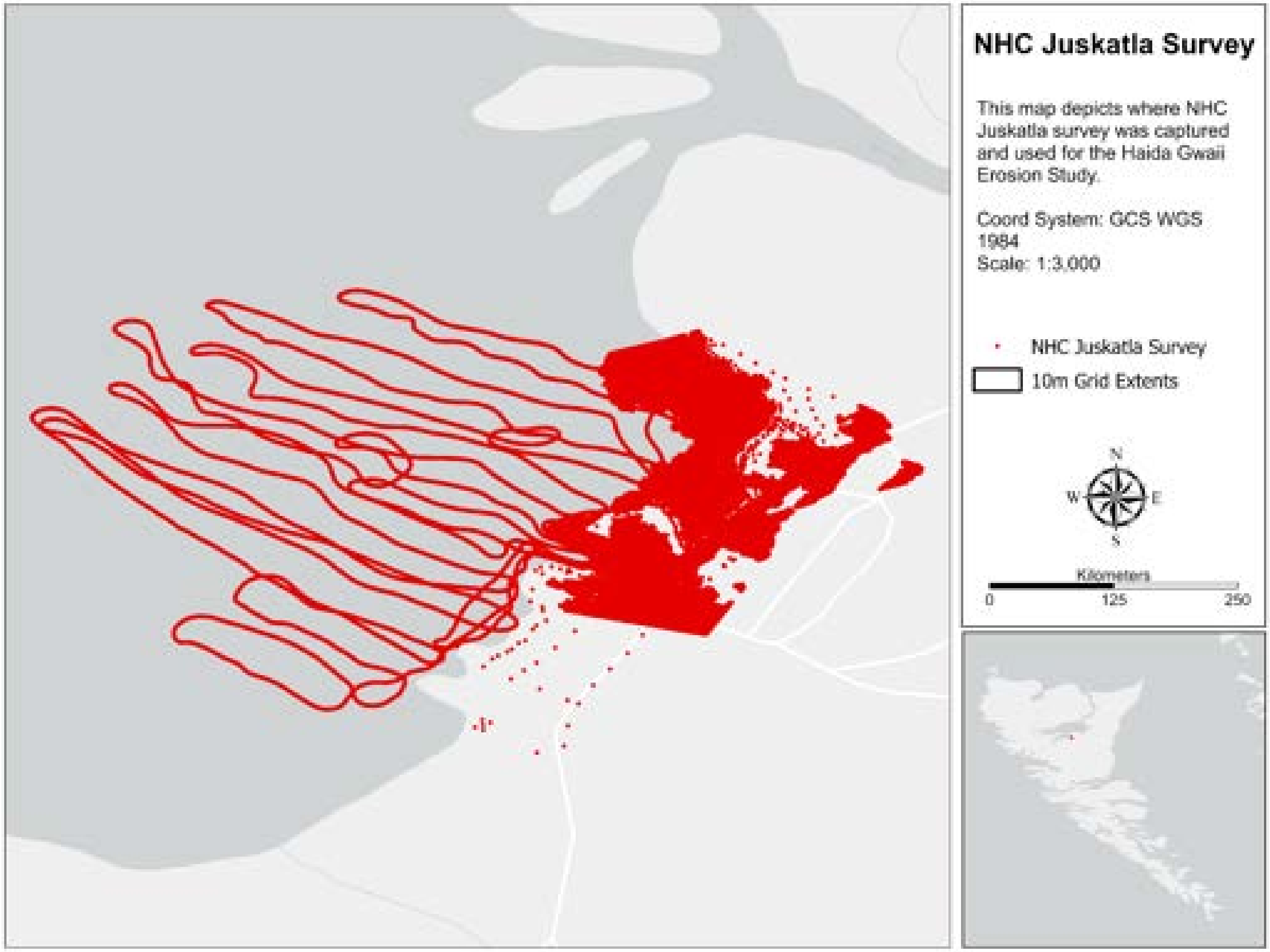

Figure 14. Map of NHC Juskatla Survey extent