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OCEAN NETWORKS CANADA

Northwest Vancouver Island Tsunami Risk Assessment - Phase 2
Digital Elevation Models Metadata Report

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1.0 Summary

Ocean Networks Canada (ONC) joined Northwest Hydraulic Consultants Ltd. (NHC) to aid in emergency preparedness for communities on northwest Vancouver Island, British Columbia. ONC's role in this project was to create integrated topographic bathymetric digital elevation models (DEMs) and tsunami models, as well as to undertake community engagement and public awareness. 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 April to December of 2022 ONC developed the DEMs, which included areas of the Strathcona Regional District (SRD) and Regional District of Mount Waddington. The purpose of these DEMs was to provide support for modelling and mapping of Tsunami inundation and hazards due to potential earthquakes from the Alaska-Aleutian and Cascadia Subduction Zones as part of the Northwest Vancouver Island Tsunami Risk Assessment project for SRD, in partnership with NHC, and several communities and First Nations.

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 in 2019 as part of a cross-border collaboration effort to develop these DEM standards. DEM creation is a complex process which aims to create a 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 minor artifacts and errors can significantly affect the quality of the tsunami and flood hazard modelling.

DEM products for the study area include two low resolution grids at 240m and 60m horizontal resolution. These were used to inform the modelling for two higher resolution 10m grids, referred to as the "Quatsino" and "Nootka" grids (Figure 1). The DEMs were created from a variety of datasets and sources, including recently captured bathymetry and LiDAR data, acquired to support this project. The extents of these DEMs, data sources, as well as data conversion and DEM creation process will be described in this document.

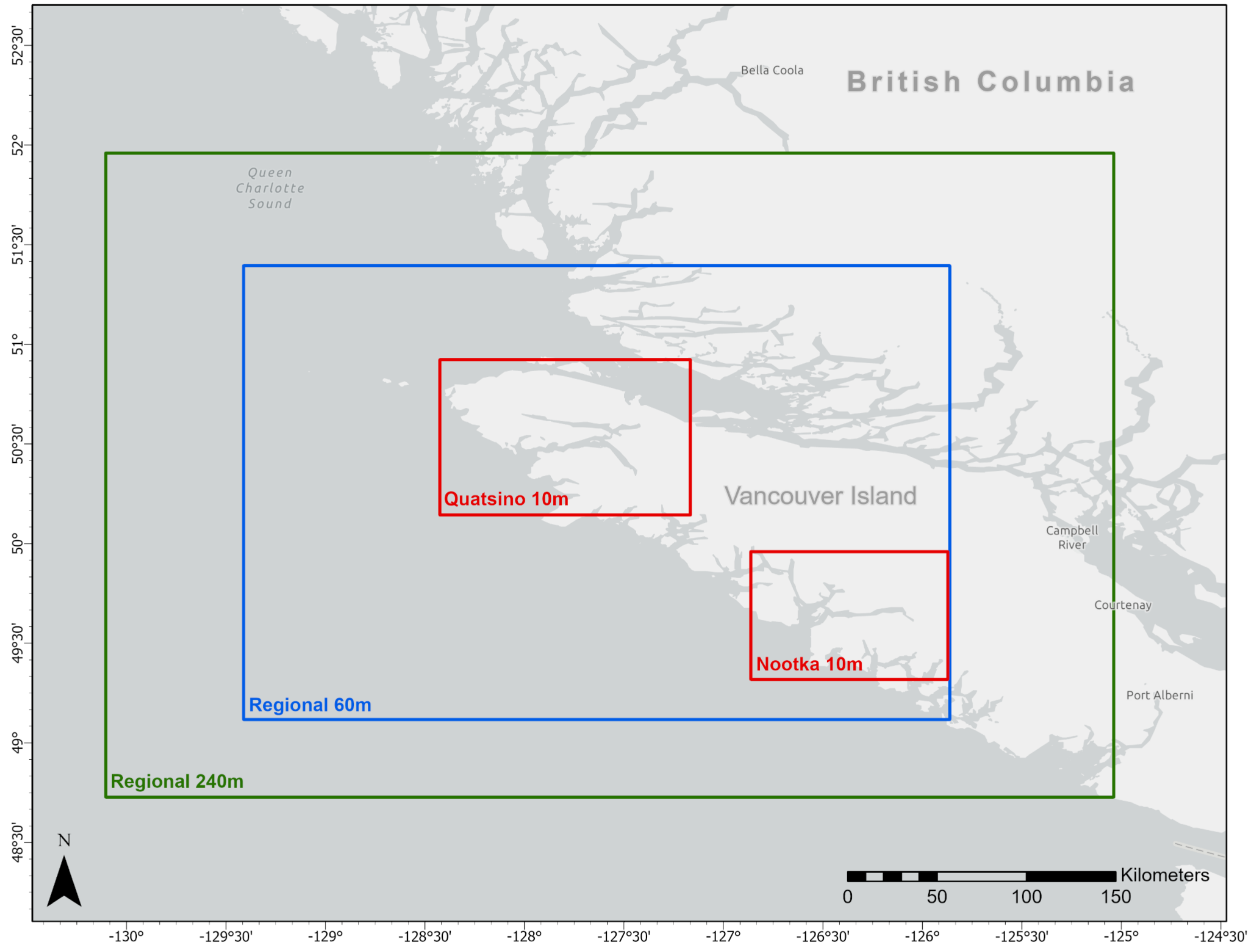


Figure 1. Map showing the extents of the two low and two high resolution DEMs created for this project.

2.0 DEM Specifications

The DEMs were built to the specifications listed in Table 1.

Table 1. Specifications for the DEMs				
Grid	Regional 240m	Regional 60m	Nootka	Quatsino
Grid Area	Northwest Vancouver Island encompassing Cape Scott to Clayoquot Sound	Northwest Vancouver Island encompassing Cape Scott to Clayoquot Sound	Northwest Vancouver Island encompassing the areas around Nootka Sound	Northwest Vancouver Island encompassing Cape Scott to Brooks Peninsula
Coverage extent (west/east/south/north)	-130.103772/-125.039247/48.727714/51.960117	-129.411/-125.862/49.117/51.395	-126.86255/-125.872144/49.31847/49.959422	-128.308306/-127.15308/50.122475/50.859865
Spatial Resolution	240m	60m	10m	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 11 different data sources (Table 2) that were integrated into one continuous DEM surface. The Canadian Hydrographic Service (CHS) coastline polyline feature class was used to clip the lower resolution Canada DEM and National Oceanic and Atmospheric Administration (NOAA) data sources so that only the land and bathymetric values, respectively, were preserved as DEM inputs for each. Please refer to pages 37-42 for maps of the datasets in Table 2.

Table 2. Data Sources					
Source/Title	**Date**	**Data Type**	**Resolution**	**Horizontal Datum**	**Vertical Datum**
Commissioned Bathymetry (Terra Remote Sensing Inc.)	2020, 2022	Bathymetric Survey	1m and variable	NAD83[1] UTM[2] 9N, EPSG[3]: 3156	CGVD2013[4]
Commissioned LiDAR (McElhanney)	2020	Topographic LiDAR Survey	1m	NAD83 UTM 9N, EPSG: 3156	CGVD2013
LiDAR (GeoBC)	2019	Topographic LiDAR	1m	NAD83 UTM 10	CGVD2013
Multibeam Bathymetry (CHS)	2000 - 2020	Bathymetric Survey	2-5m	WGS[6] 1984	Chart Datum (LLWLT[7])
Singlebeam Bathymetry (CHS)	1934 - 2010	Bathymetric Survey	Varies	WGS 1984	Chart Datum (LLWLT)
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 DEM (DFO/NRCan)	2021	DEM Surface	10m	WGS 1984	Chart Datum (LLWLT)
Canadian Digital Elevation Model (NRCan)	1945 - 2011	DEM Surface	0.75 arc-second (~20m)	NAD83 (CSRS)	MSL[8] (NAD83)
Bathymetric DEM of British Columbia, Canada (NOAA)	1930 - 2012	Bathymetric Surface	3 arc-second (~93m)	WGS 1984	MSL
Simulated Points (ONC)	2022	Bathymetric and Topographic Points	Variable	WGS 1984	CGVD2013
High Water Line for	2013	Coastline	N/A	NAD83	N/A

British Columbia (CHS)		Shapefile			

[1] North American Datum
[2] Universal Transverse Mercator
[3] European Petroleum Survey Group
[4] Canadian Geodetic Vertical Datum
[5] Canadian Spatial Reference System
[6] World Geodetic System
[7] Lower Low Water Large Tide
[8] Mean Sea Level

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 into the DEMs and meet the specifications in Table 1. 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 & MB-Grid
- Geospatial Data Abstraction Library (GDAL)
- Bathymetry smoothing python script
- ArcGIS Pro
- Global Mapper
- CHS vertical datum conversion grid

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

Commissioned Bathymetry, 2020 & 2022 (Terra Remote Sensing Inc.)

Geospatial data acquisition company Terra Remote Sensing Inc. (TRSI) was contracted to capture bathymetry data for the Zeballos Inlet, Tahsis Inlet, Strange Island vicinity, Gold River, Quatsino, Winter Harbour, Port Alice, and Holberg, due to previously poor data availability in those key areas. The 2020 multibeam data for Phase I was delivered in four XYZ files at 1m horizontal resolution and singlebeam data was delivered in two XYZ files with variable resolution. The data delivered from 2022 for Phase II contained four XYZ files that were a combination of multibeam and singlebeam, and one variable resolution XYZ singlebeam for Gold River.

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

1. Converted the horizontal datum from NAD83 UTM Zone 9N to WGS-1984 in decimal degrees, and XYZ format, using the cs2cs tool from LAStools.
2. Split the larger XYZ files into more manageable data chunks using the GMT block median tool.
3. Generated .inf files for each XYZ file.
4. Created a datalist for the processed bathymetry files.

Commissioned LiDAR (McElhanney)

As part of Phase I of the project, the multi-disciplinary survey company McElhanney was contracted to capture LiDAR data throughout the study area as no publicly available data existed in the key areas. Data was delivered in 436 .las format files at a horizontal resolution of 1m.

- 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 extracted and the data were converted to XYZ for integration into the DEM. However, some additional processing was necessary to remove some erroneously classified bare earth points over areas of water before the datasets underwent processing for the DEM integration. This step was accomplished by viewing the LiDAR points in Global Mapper and deleting swaths of erroneous points that remained over known deep water areas. In addition, some points were deleted near Gold River that appeared to be from buildings and tall trees that were incorrectly classified as bare earth.

After the bare earth data was verified, the remaining points were processed and converted into the format required for the DEM.

1. Extracted the bare earth points using the las2txt tool 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 LAStools.
3. Generated .inf files for each of the XYZ files.
4. Created a datalist for the processed LiDAR dataset.

LiDAR (GeoBC)

GeoBC Topographic LiDAR is publicly available and was obtained from the GeoBC portal[1]. Data was obtained as .laz files and covers a large swath of area spanning the majority of the Quatsino grid, and a small portion of the southeast of the Nootka grid. This dataset consisted of 1169 .las format files at a horizontal resolution of 1 metre.

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: UTM Zone 10 North
- Vertical Datum: CGVD2013
- Vertical Units: Metres

The points classified as bare earth (ground only, vegetation and buildings removed) were extracted and the data were converted to XYZ for integration into the DEM. However, some additional processing was necessary to remove some erroneously classified bare earth points over areas of water before the datasets underwent processing for the DEM integration. This step was accomplished by viewing the LiDAR points in Global Mapper and deleting swaths of erroneous points that remained over known deep water areas. The incorrectly classified points covered a significant amount of area in much of the Quatsino grid and some of the Nootka grid.

After the bare earth data was verified, the remaining points were processed and converted into the format required for the DEM.

1. Extracted the bare earth points using the las2txt tool 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 LAStools.
3. Generated .inf files for each of the XYZ files.
4. Created a datalist for the processed LiDAR dataset.

Multibeam Bathymetry (CHS)

Through a data agreement with CHS, multibeam bathymetry within the study area was obtained. The data was delivered in .CSAR format in two files; one for 2m resolution surfaces, and the second for 5m resolution.

- Horizontal Datum: WGS-1984

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

- 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 tab-delimited text file 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. Split the converted XYZ files into more manageable data chunks using the GMT block median tool.
5. Generated .inf files for each XYZ file.
6. Created a datalist for the processed CHS multibeam dataset.

Singlebeam Bathymetry (CHS)

Through the same data agreement with CHS mentioned above, singlebeam bathymetry within the study area was obtained. The data was delivered in .CSAR format. This was a very large point dataset that varied in resolution across the entirety of the study area, with the highest resolution in the inlets and concentrated around communities, and the lowest in the open ocean offshore.

- 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 singlebeam points as a text file, tab-delimited, with the data in geographic coordinates in decimal degrees.
2. Converted the data to XYZ.
3. Converted the vertical datum from chart datum to CGVD2013 using a conversion grid provided by CHS.
4. Generated .inf files for the 1 XYZ file.
5. Created a datalist for the processed CHS singlebeam dataset.

However, during the course of this project it was discovered that the singlebeam points were also integrated into the multibeam package that was delivered by CHS. This made the use of the singlebeam dataset in the DEMs unnecessary.

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

CHS has publicly available Non-Navigational (NONNA) bathymetric data from their data portal in both 10m and 100m horizontal resolution (https://data.chs-shc.ca/map). The NONNA-10 (10m resolution) for the study area 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. Below is an example of this conversion:
    a. Original data: 49-00-00.712N 126-02-57.407W 60.09020.
    b. 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.
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 (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 the topographic areas being well covered by LiDAR throughout the study area.

[2] https://open.canada.ca/data/en/dataset/e6e11b99-f0cc-44f7-f5eb-3b995fb1637e

- 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
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

Additional processing:
This dataset was produced with data from many sources and the quality of all the inputs and quality assurance is unknown. Some areas of this dataset were trimmed, particularly along the coasts in key areas of the Nootka DEM, and obvious outliers were removed before it was integrated into the DEMs as part of this project.

Canadian Digital Elevation Model (CDEM)(NRCan)

Data was downloaded via FTP in GeoTIFF format, courtesy of the Government of Canada - Natural Resources Canada[3]. This data acquisition resulted in 9 GeoTIFFs (the number of CDEM grids that intersected the study area) 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

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

1. Removed cells with a standard “no data” value of -32767 from all files.

[3] Ftp.geogratis.gc.ca/pub/nrcan_rncan/elevation/cdem_mnec

2. Split the 9 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 1174 text file format XYZ files, tab delimited, which were organized into 9 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. CADEM092C
    b. CADEM092E (later reprocessed, see note below)
    c. CADEM092F
    d. CADEM092K
    e. CADEM092L (later reprocessed, see note below)
    f. CADEM092M
    g. CADEM092N
    h. CADEM102I (later reprocessed, see note below)
    i. CADEM102P

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 CDEM and the LiDAR. To remedy this issue, the CDEM subsets that overlapped with the LiDAR in key locations of the study area 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.

In addition, subset 092E was suspected to have unreliable values at Canton Creek. Therefore, a small area of unrealistically high elevations within the creek area were removed from the dataset.

Bathymetric DEM of British Columbia, Canada (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

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

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 very coarse and conversion would have negligible impact on the final DEM. The difference between the two datums is 1-3 metres.
2. Clipped the GeoTIFF to the coarsest extents of the study area, -129.8/-125.2/51.3/48.4.
3. Split and converted 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 an issue with the coarse resolution of the ~90m NOAA data in resolving the depths 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 data being averaged from a large range of values due to the steep nature and sudden depth changes over small horizontal distances in these coastal fjords. Since these values were not 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 3-5 above and was used for integration into the lower resolution DEM surfaces.

Simulated points from ONC

Gold River

Simulated points were created at Gold River to mitigate issues observed in the DEM during the modelling process. Observed issues, such as large vertical variations and inconsistencies in the river bed, were caused by sparsely populated LiDAR (likely due to heavy vegetation coverage hindering canopy penetration) along the shoreline upriver from the industrial terminals at Muchalat Inlet. This was remedied by creating a small simulated point file along the river edge, with the most points added along the south bank. Values for the simulated elevations were estimated based on the nearby LiDAR that did capture the river bank elevations. Points were created manually using Global Mapper. Figure 2 shows the segment of Gold River before and after the addition of manual points to the model. This image also shows the result of removing LiDAR (McElhanney) points that were erroneously classified as ground, but were likely representing tall vegetation values.

1. Evaluated where there were gaps in the LiDAR data in problem areas

2. Used Global Mapper to create a new XYZ point file
3. Added points and assigned elevation values
4. Exported as an XYZ file
5. Generated .inf file and created datalist for the simulated Gold River points

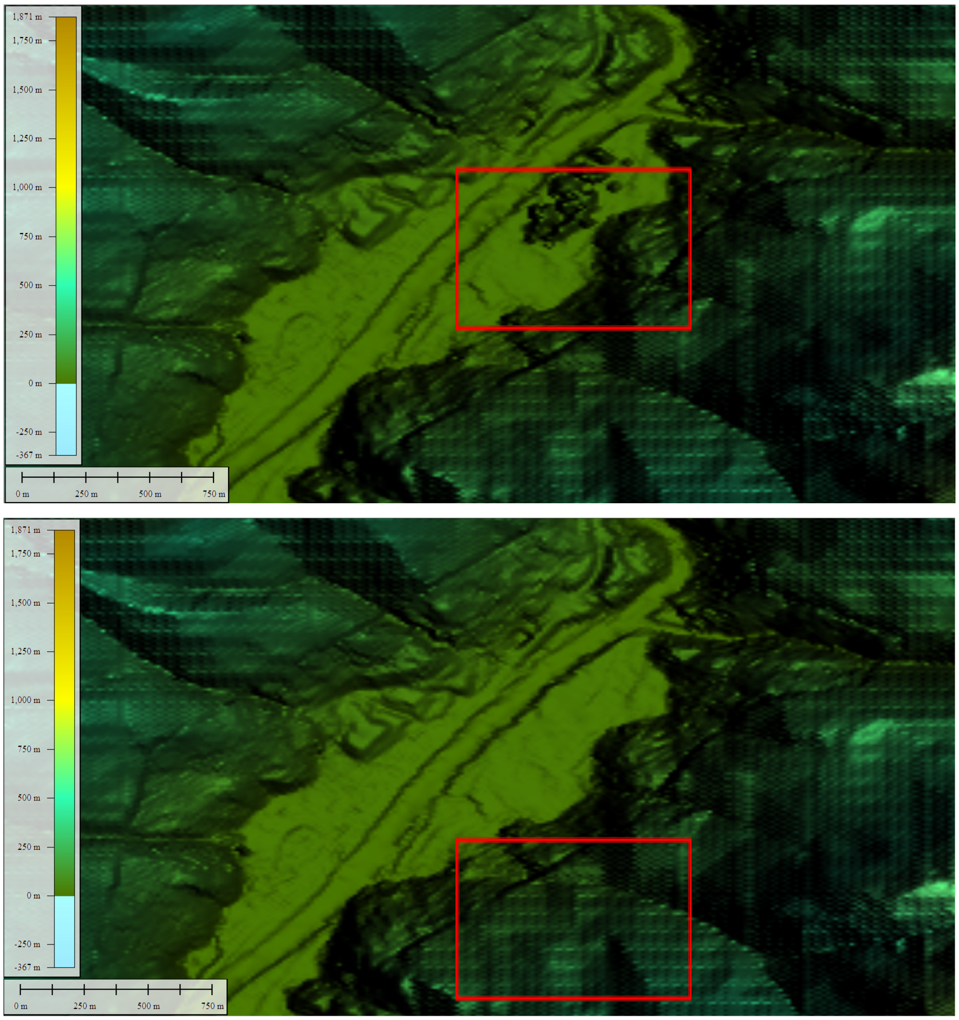


Figure 2. Comparison of the Nootka 10m DEM before and after simulated points were added along the river bank to supplement sparse lidar. The image above shows the DEM prior to the removal of erroneous lidar points and the addition of the simulated points while the image below is the DEM after the modifications.

Critter Cove

A narrow passageway connecting a small body of water to Critter Cove was not able to be resolved in the 10m Nootka DEM due to a lack of high resolution bathymetry data availability. Simulated points were added in the passageway and along the coastline in order to improve the model in this area. A value of -3.5m was chosen for these simulated points and was based on the depth of the few bathymetry data points available in the narrow channel. Points were created manually using Global Mapper. Refer to Figure 3 to see the difference before and after the simulated points were added at Critter Cove.

1. Evaluated where there were gaps in the bathymetry
2. Used Global Mapper to create a new XYZ point file
3. Added points and assigned elevation values
4. Exported as an XYZ file
5. Generated .inf file and created datalist for the simulated Critter Cove points

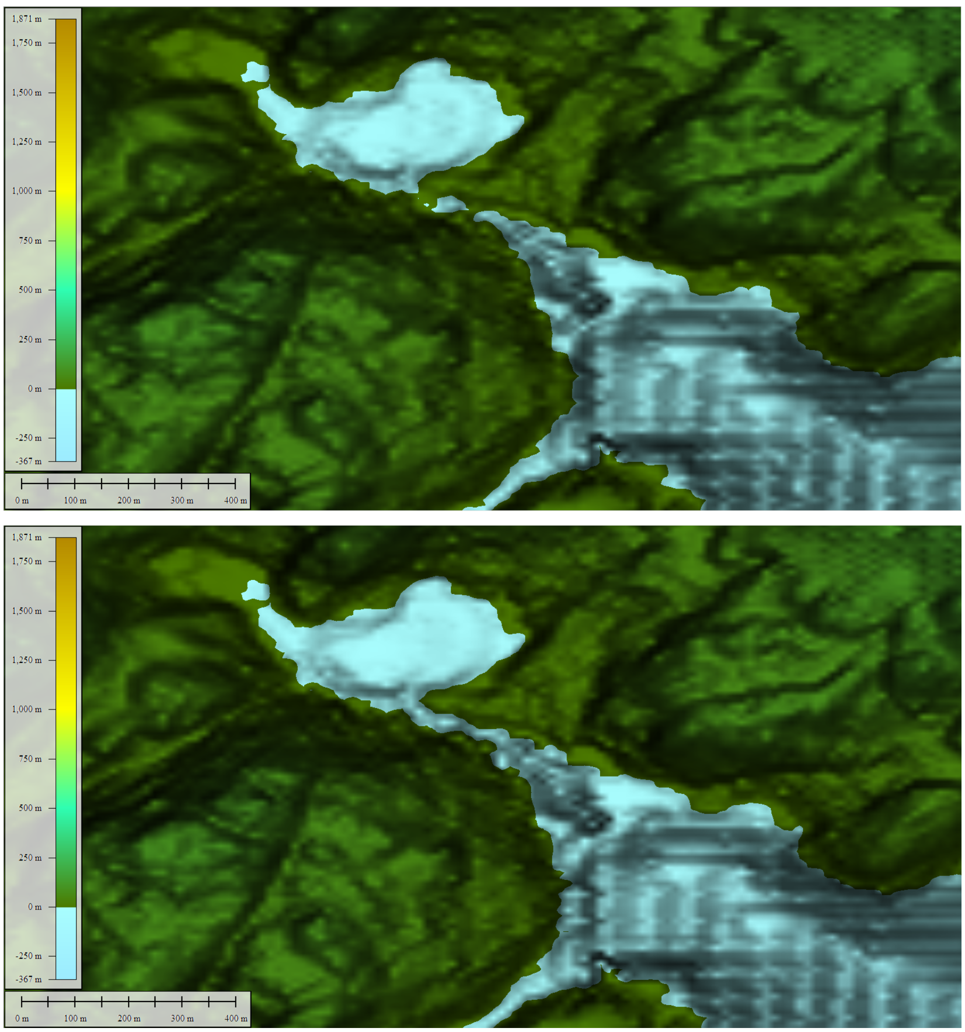


Figure 3. Comparison of the Nootka 10m DEM before and after simulated points were added at Critter Cove. The image above shows the DEM prior to the addition of the simulated points while the image below is the DEM after the modifications.

Cougar Creek

A bridge feature was removed from the McElhanney LiDAR, but without any ground points for the creek below the bridge, the DEM model produced an obstruction in Cougar Creek in the Nootka 10m DEM. To remedy this, simulated points were added along the creek and under the bridge with a value of 2.5m determined based on nearby LiDAR points. The addition of these points significantly lowered the vertical obstruction at this location. Points were created manually using Global Mapper. Figure 4 provides a visual comparison of Cougar Creek before and after the addition of the simulated points.

1. Evaluated where there were gaps in the LiDAR data in problem areas
2. Used Global Mapper to create a new XYZ point file
3. Added points and assigned elevation values
4. Exported as an XYZ file
5. Generated .inf file and created datalist for the simulated Cougar Creek points

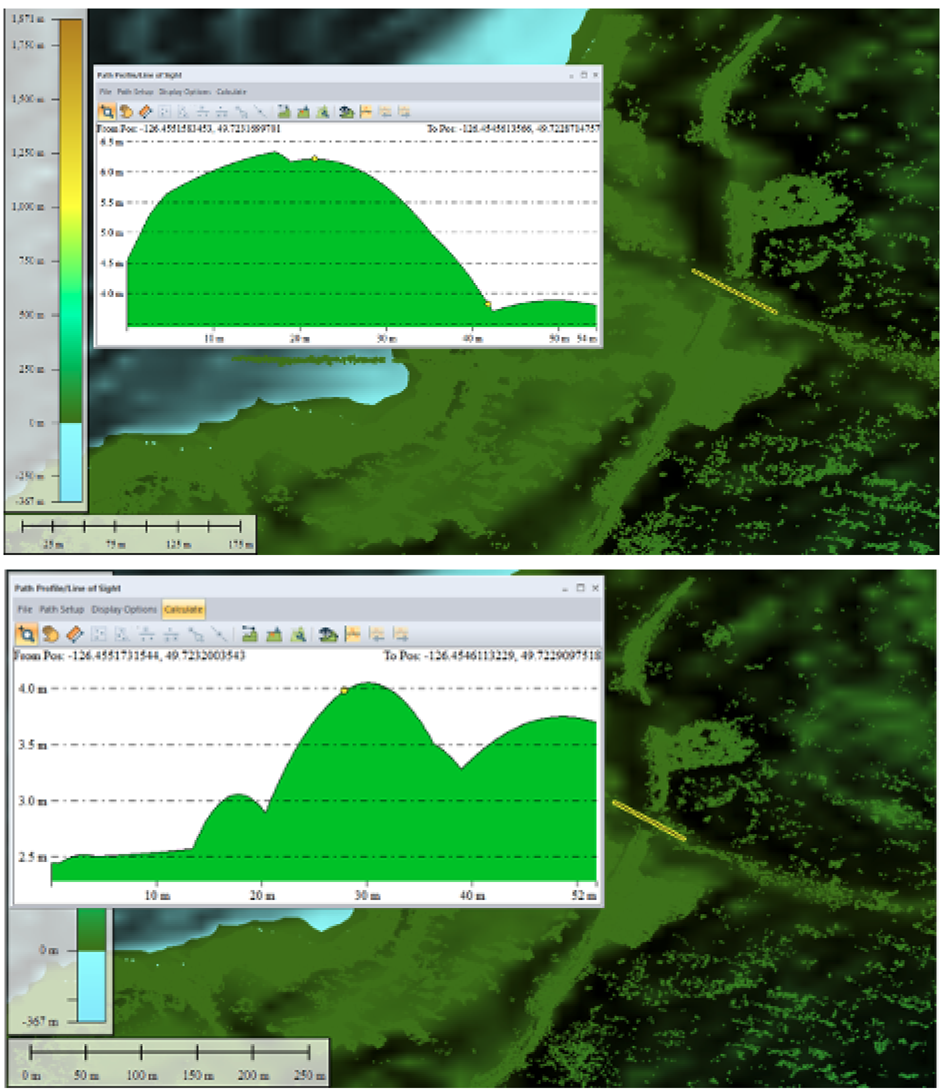


Figure 4. Comparison of the Nootka 10m DEM before and after simulated points were added along Cougar Creek. The image above shows the DEM, with a cross-section along the creek at the bridge, prior to the addition of the simulated points while the image below is the DEM and cross-section after the modifications.

Santa Boca Inlet

A narrow passageway connecting a small body of water at Santa Boca Inlet was not able to be resolved in the 10m Nootka DEM due to the lack of high resolution bathymetry data available. Simulated points were added in the passageway and along the coastline, including some topographic elevations, in order to improve the model in this area.

Bathymetric simulated points were created by using ArcGIS Pro to draw a polygon containing the narrow passage and then utilizing the ‘Create Random Points’ tool to generate dense points within the polygon. A value of -1.0 metres was chosen for the bathymetric simulated points and was based on the depth of the few bathymetry data points available in the narrow channel. The point feature class was exported as a .txt, which was then converted to XYZ.

Elevation values for the topographic simulated points were selected based on the nearest surrounding LiDAR and points were created manually using Global Mapper. The addition of topographic elevations was necessary in this area due to sparse LiDAR coverage on the southern slope bordering the passage, which was contributing to the challenges in modelling this narrow inlet. Refer to Figure 5 to see the difference before and after the simulated points were added at Santa Boca Inlet.

1. Evaluated where there were gaps in the bathymetric and topographic data
2. Used Global Mapper and ArcGIS Pro to create new XYZ point files (bathymetric and topographic)
3. Added points and assigned elevation values
4. Exported as, or converted to, XYZ files
5. Generated .inf files and created datalists for the simulated Santa Boca Inlet points

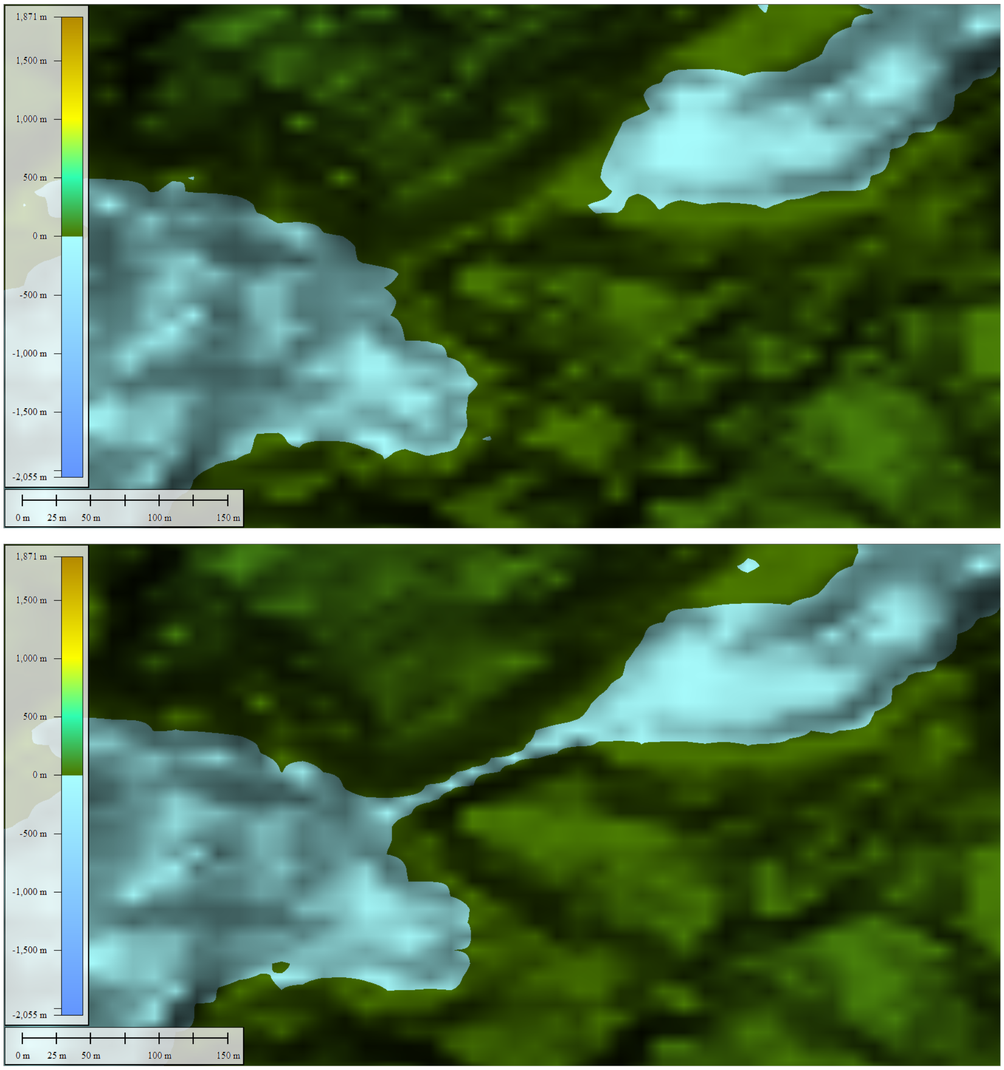


Figure 5. Comparison of the Nootka 10m DEM before and after simulated points were added at Santa Boca Inlet. The image above shows the DEM prior to the addition of the simulated points while the image below is the DEM after the modifications.

Deserted & Yoquot Lakes

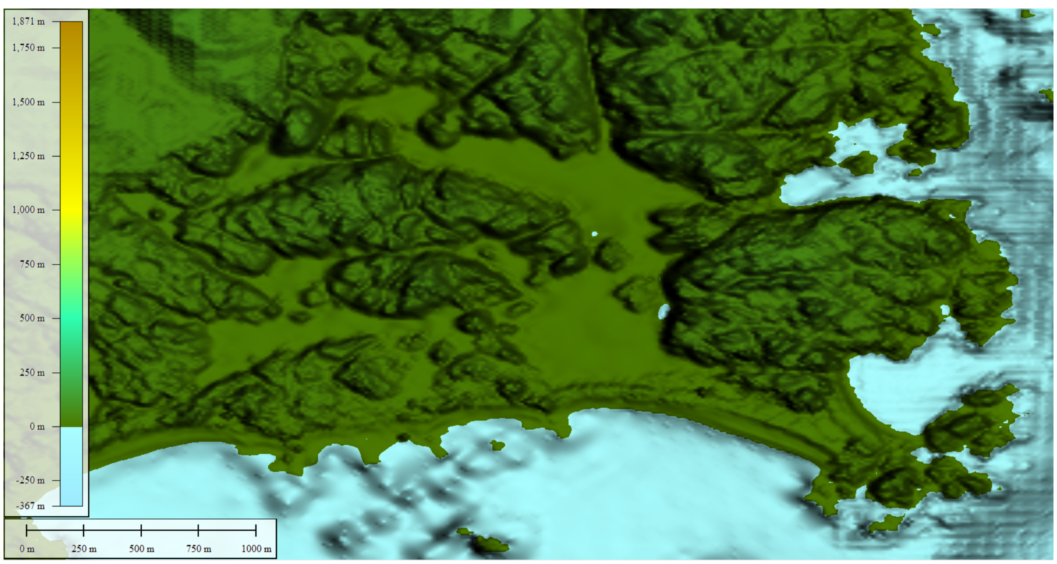
Bathymetric data for lakes was not available in the study area which led to lakes within the Nootka DEM extent that contained elevation spikes and bumpy surface texture. The non-flat nature of two of these lake surfaces was identified as having potential impact on the tsunami modelling, therefore, a hydro-flattening process using simulated points was undertaken. The hydro-flattening process involved accessing a provincial freshwater lakes atlas shapefile[5], and extracting only the two lakes of interest. ArcGIS Pro tool 'Create Random Points' was then used

5 https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-lakes/resource/be0fa7e3-75d1-4514-8148-30bd110c6179

to fill the lake polygons with dense points. A point density of 20,000 points was used as this provided an average of 5m separation between the points.

The selection of elevation values to apply to the points was accomplished by creating a buffer of 1m around the lakes polygons, and then selecting the McElhanney LiDAR points that were within that buffer zone. The elevation values of the LiDAR within the buffer were sorted, and the average of the 10 lowest elevation points of each lake were calculated. The 10 lowest points were also plotted over satellite imagery to ensure they were not outliers before the values were applied to the simulated points. See Figure 6 for a comparison of Yoquot Lake before and after the application of the simulated points.

1. Extracted lake polygons from provincial atlas
2. Used "Create Random Points" tool in ArcGIS Pro to fill the polygons with dense points
3. Added XY coordinates to the points and applied elevation values
4. Exported as .txt and then converted to XYZ
5. Generated .inf files and a datalist for the simulated lake points



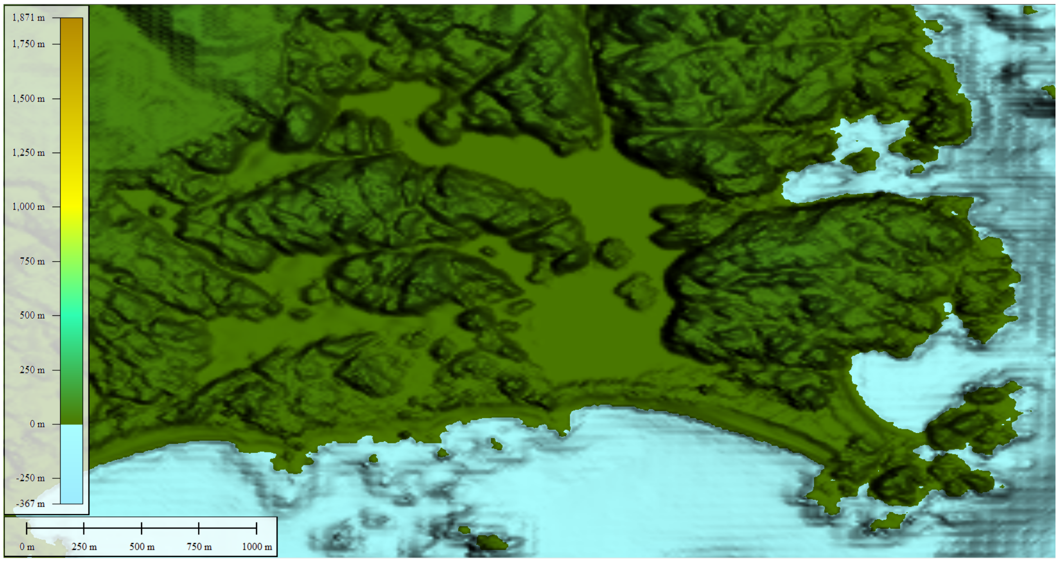


Figure 6. An example comparison for before (above) and after (below) of the hydro-flattening performed at Yoquot Lake.

Ahwhichaolto Inlet

Located near Winter Harbour, Ahwhichaolto Inlet had no high resolution bathymetry data, despite it being connected to the ocean and an area that experiences tidal flooding. While this area is not of high importance in this project, it was decided to hydro-flatten the inlet to improve the visual aesthetic of the DEM, and mitigate any issues the original elevation discontinuities and spikes in this area could have on further use of the Quatsino DEM. Similar to the method for the lake simulated points above, hydro-flattening involved creating simulated points in the inlet. Bathymetric values of -1.0m were applied to these simulated points based on the nearest CHS dataset values and examination of the underlying charts.

1. Created a polygon encompassing Ahwhichaolto Inlet
2. Used “Create Random Points” tool in ArcGIS Pro to fill the polygon with very dense points (over 1,000,000 at 1m spacing)
3. Added XY coordinates to the points and applied an elevation value
4. Exported as .txt and then converted to XYZ
5. Generated .inf files and a datalist for the simulated Ahwhichaolto Inlet points

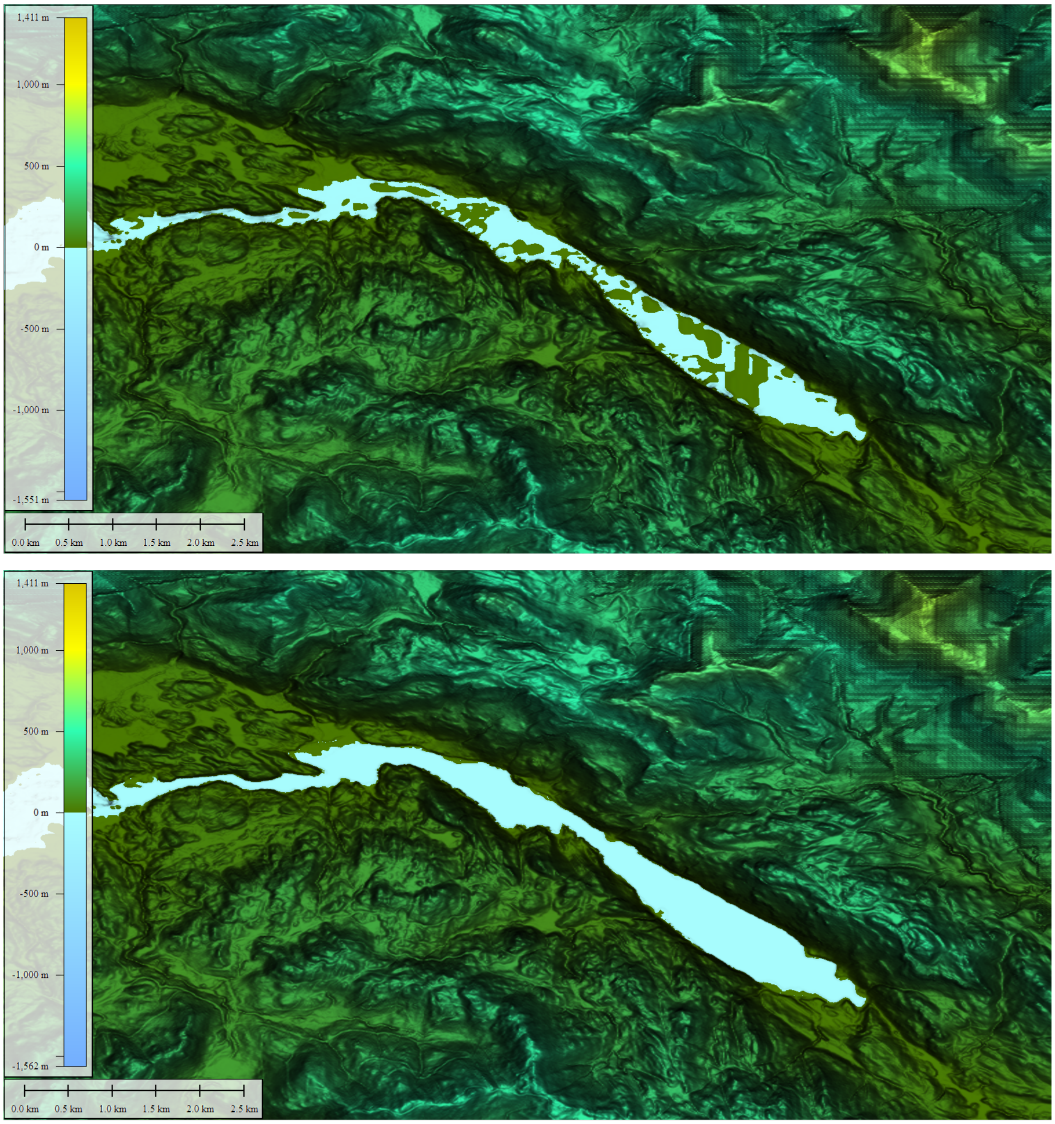


Figure 7. An example comparison for before (above) and after (below) of the hydro-flattening performed at Ahwhichaolto Inlet.

High Water Line for British Columbia (CHS)

A polyline vector feature class used by CHS that defines the coastline at the Higher High Water Large Tide mark in BC's tidal waters. This dataset is derived from numerous sources including satellite imagery and other CHS data products. 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 12 datasets, generated from the input data sources in Table 2, 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 3 below lists the datasets in the master datalist for each high resolution DEM, and the weights assigned to each for this project. Lower resolution DEMs used the same weights as the Nootka DEM.

Table 3. Dataset weights in Nootka and Quatsino Datalists

Dataset Name	Weight (Nootka)	Weight (Quatsino)
Commissioned LiDAR (McElhanney)	20	N/A
LiDAR (GeoBC)	15	50
Commissioned Bathymetry, 2020 & 2022 (TRSI)	20	30
Gold River Bathymetry 2022 (TRSI)	50	N/A
Multibeam Bathymetry (CHS)	15	20
Singlebeam Bathymetry (CHS) (Excluded from high resolution DEMs)	15	15
Non-Navigational (NONNA-10) Bathymetric Data (CHS)	3	10
Canada West Coast Topo-Bathymetric DEM (DFO/NRCan)	1	1
Bathymetric DEM of British Columbia, Canada (NOAA) (Excluded from high resolution DEMs)	0.1	0.1

CDEM (NRCan)	1	1
CDEM-Clipped to LiDAR (NRCan)	1	1
Simulated Points - Bathymetric (ONC)	150	150
Simulated Points - Topographic (ONC)	100	N/A

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.

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 (MBARI). 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 most of the study area, some of the bathymetric areas of the DEMs contain visible artifacts as a result of stitching together the various data sources, particularly those of differing resolutions. There is a smoothing script available from NOAA that can be used to mitigate the abrupt features at the edges of the differing input sources. This script implements a user-specified smoothing factor to smooth only the bathymetric values of the DEM surface (values below 0m). However, it was decided not to apply the smoothing to any of the grids in this project.

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 inspections were performed. The software programs ArcGIS Pro and Global Mapper were used for most of these checks. For the first inspections, Global Mapper was used to visualize the DEMs with hillshades and colour shading to determine the elevation and depth changes, and compare these with satellite imagery of the area to determine if the model was a reasonable representation of reality. These comparisons aided in finding some of the initial issues that led to the abovementioned reprocessing for 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. Charts also confirmed deeper seafloor depths where data can be sparse.

Following the depth comparisons between the charts and the DEM models, satellite imagery was used to compare the coastlines between the models and reality (Figure 8). 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 inspections ensured that islands in the DEMs are real, rather than artifacts in the DEMs. It should be noted that the CHS charts were also used to confirm that rocks and islands in the DEM were realistic. 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.

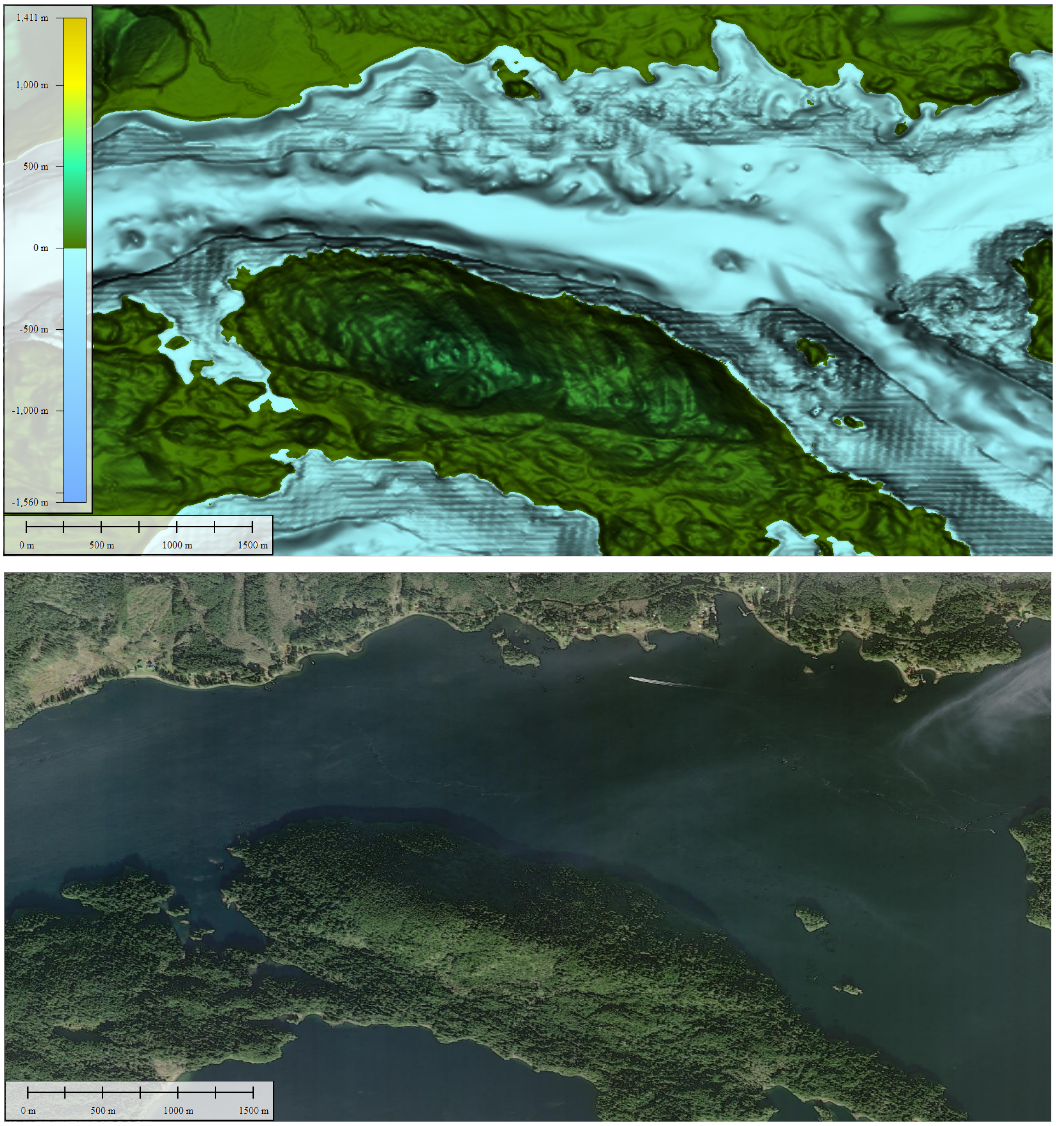


Figure 8. Image comparing a segment of the Quatsino 10m DEM with satellite imagery in Global Mapper.

In addition to the above mentioned methods, the DEM elevations were also compared to the high resolution raw data inputs to ensure that the best available data was accurately integrated and represented in the final products.

5.2 Dataset limitations

Due to the sparse coverage of high resolution data in some parts of the study area, lower resolution datasets were used to fill the gaps where there was no high resolution data available. For example, NOAA's Bathymetric DEM of British Columbia was used to fill the gaps in the open ocean for lower resolution DEMs. 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.

Another dataset used to fill bathymetric gaps was the Canada West Coast DEM. This proved to be an essential piece in some areas, such as parts of Muchalat Inlet and King Passage (Figure 9) where CHS data was unavailable. However, this dataset created barrier issues at the boundaries where the West Coast DEM met with the higher resolution datasets (Figure 10). Additionally, it is unknown exactly what data was used to create this dataset, or how it was integrated and quality checked. There were a few instances where parts of the West Coast DEM had to be edited before it was integrated into the high resolution DEMs for this project. These edits were made to remove suspicious rocks and shallow depths that did not match with what was seen in co-located higher resolution data, or was not noted in the charts. Despite some of the drawbacks to using this dataset, it filled necessary inshore gaps where the CHS data was significantly sparse, or lacking entirely, and the NOAA data was excluded nearshore due to the abovementioned low resolution.

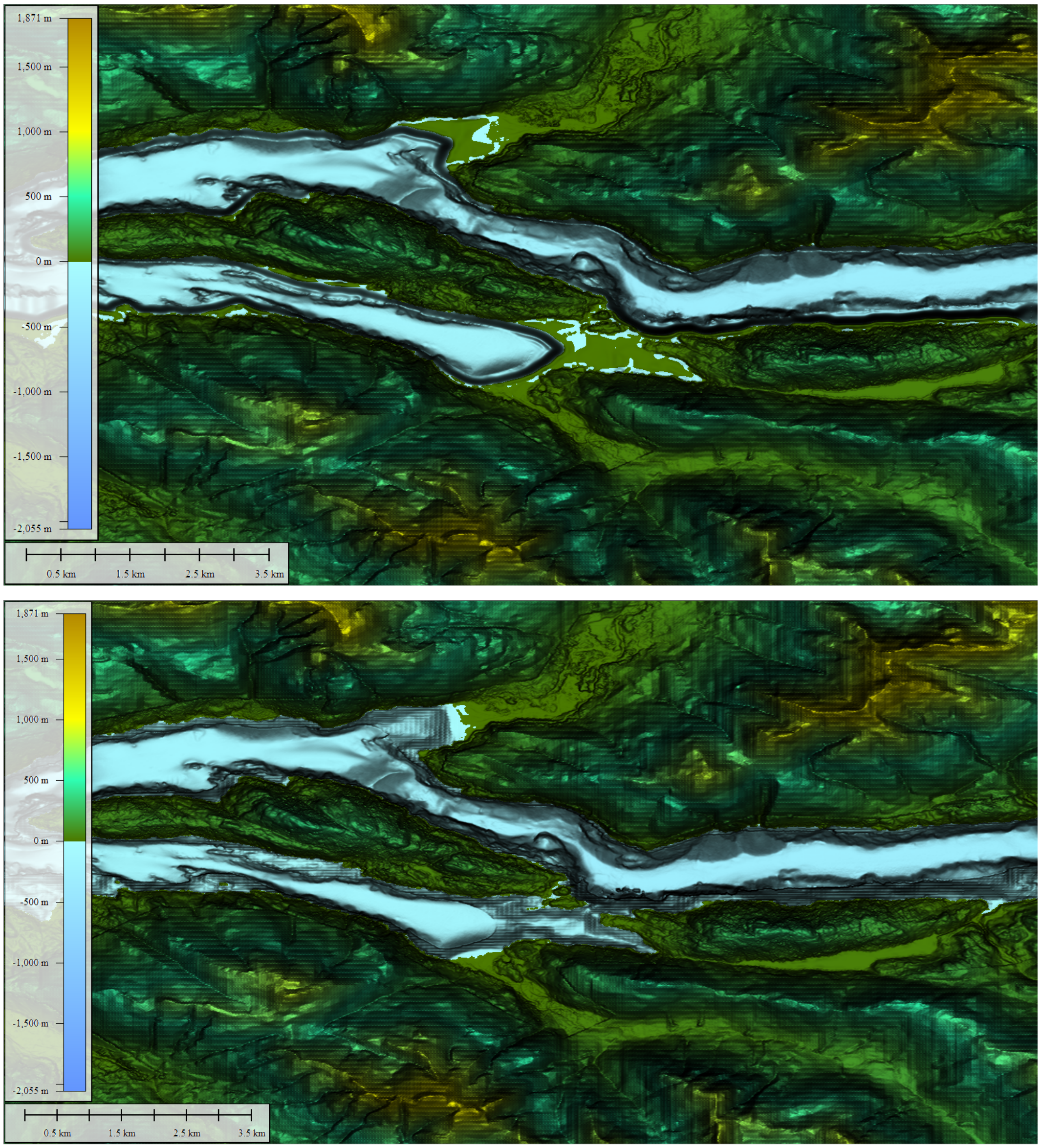


Figure 9. King Passage without the inclusion of Canada West Coast DEM (above) and the same area with it included (below).

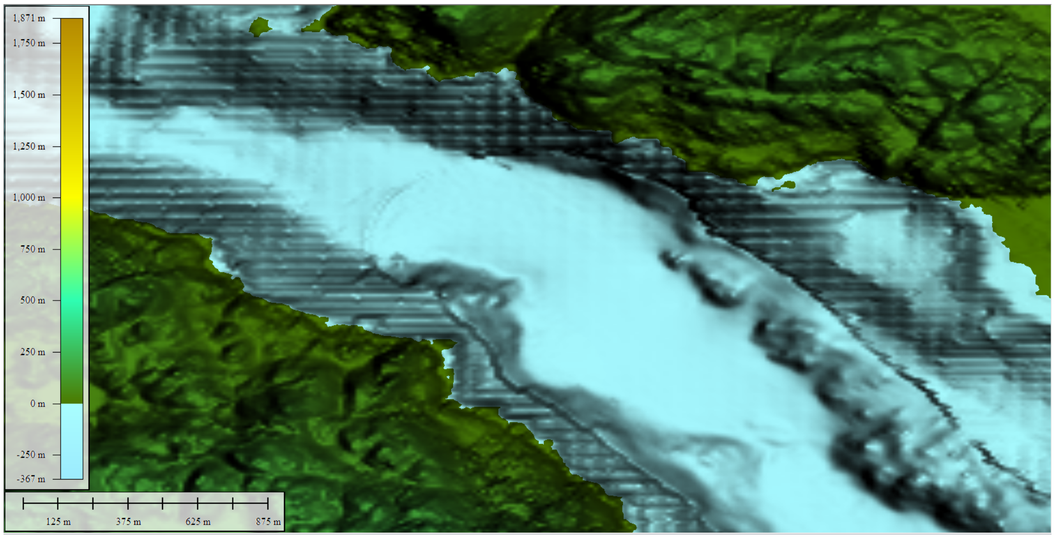


Figure 10. Example of a barrier effect where the Canada West Coast DEM converges with the higher resolution CHS multibeam.

Similarly, to fill the sparse coverage over the land topography, the lower resolution Canadian Digital Elevation Model (CDEM) was used. Figure 11 shows the accuracy of the CDEM, as specified by NRCan, to be between 0-20 metres throughout most of the study area. This product is reasonably reliable for most mapping uses, but there were instances where the roads, coastline, and other important finer details were not accurately represented in the models due to the lower resolution. Fortunately, the high resolution 1m LiDAR datasets covered most of the study area at the lower elevations, so the CDEM was only used to model higher elevations where the LiDAR was not captured. However, there was a low elevation area upstream of Canton Creek, not far from the outflow into Tlupana Inlet, that showed irregularities in the CDEM and was not covered by high resolution LiDAR. The suspected erroneous CDEM data in the area was removed from the project, but it should be noted that this area has additional uncertainties.

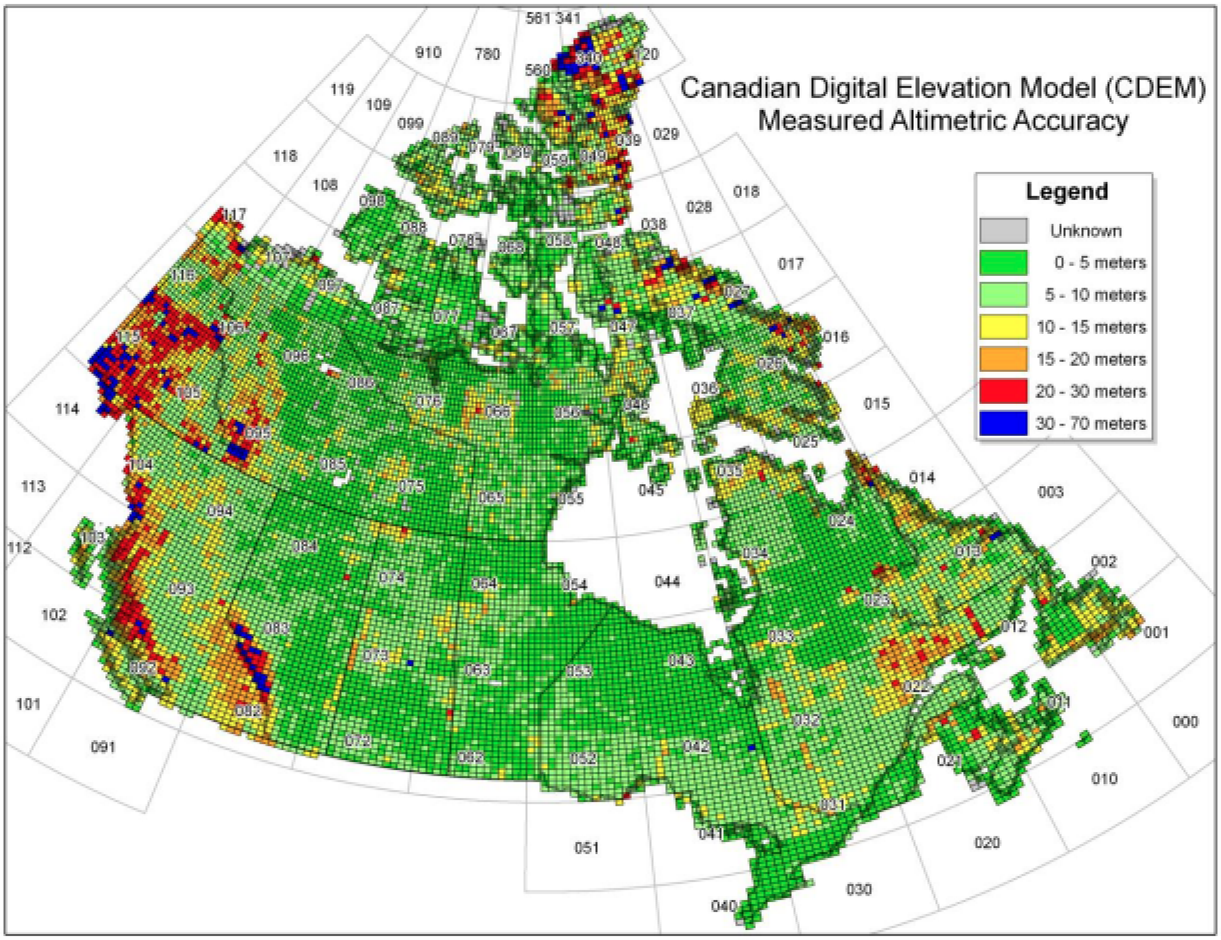


Figure 11. Natural Resources Canada map showing CDEM altimetric accuracy from the Canadian Digital Elevation Model Product Specifications report.

Additionally, it was found that some finer features, such as rivers and streams, can be poorly represented in the output DEMs due to some of the lower resolution datasets and a lack of freshwater bathymetry. In areas without adequate coverage of high resolution data, these smaller features may not be accurately represented. In this project, Gold River received enhanced scrutiny due to the proximity of major infrastructure. Improvements to this area included the capture of bathymetric data at the river mouth, and thorough quality checks of the resultant DEM. However, the additional bathymetry only extends a short distance upriver due to the challenges capturing river bathymetry with traditional methods. In order to aid with modelling this area, simulated points were added to an upriver portion of Gold River. It must be noted that these simulated points are only estimations, and this can introduce additional uncertainties to this area. Therefore, without additional field data to confirm estimated elevation values, caution should be exercised when using these DEMs for additional modelling and mapping purposes at Gold River, as well as other areas where simulated points were used.

As mentioned previously, some of the GeoBC LiDAR were found to have incorrectly classified some of the LAS files, so manual fixes were implemented in order to remove the misclassified data from the final DEM models. There were 341 LAS files included in this project where land values were incorrectly classified over known deeper bathymetric areas and this led to some unrealistic flat plateaus in the open ocean and inland fjords in the initial DEM models. These incorrect points in the LAS files were identified and then manually removed. The DEM was recreated with the fixed LAS files so that the final models no longer included these false shallow ocean plateaus (Figure 12).

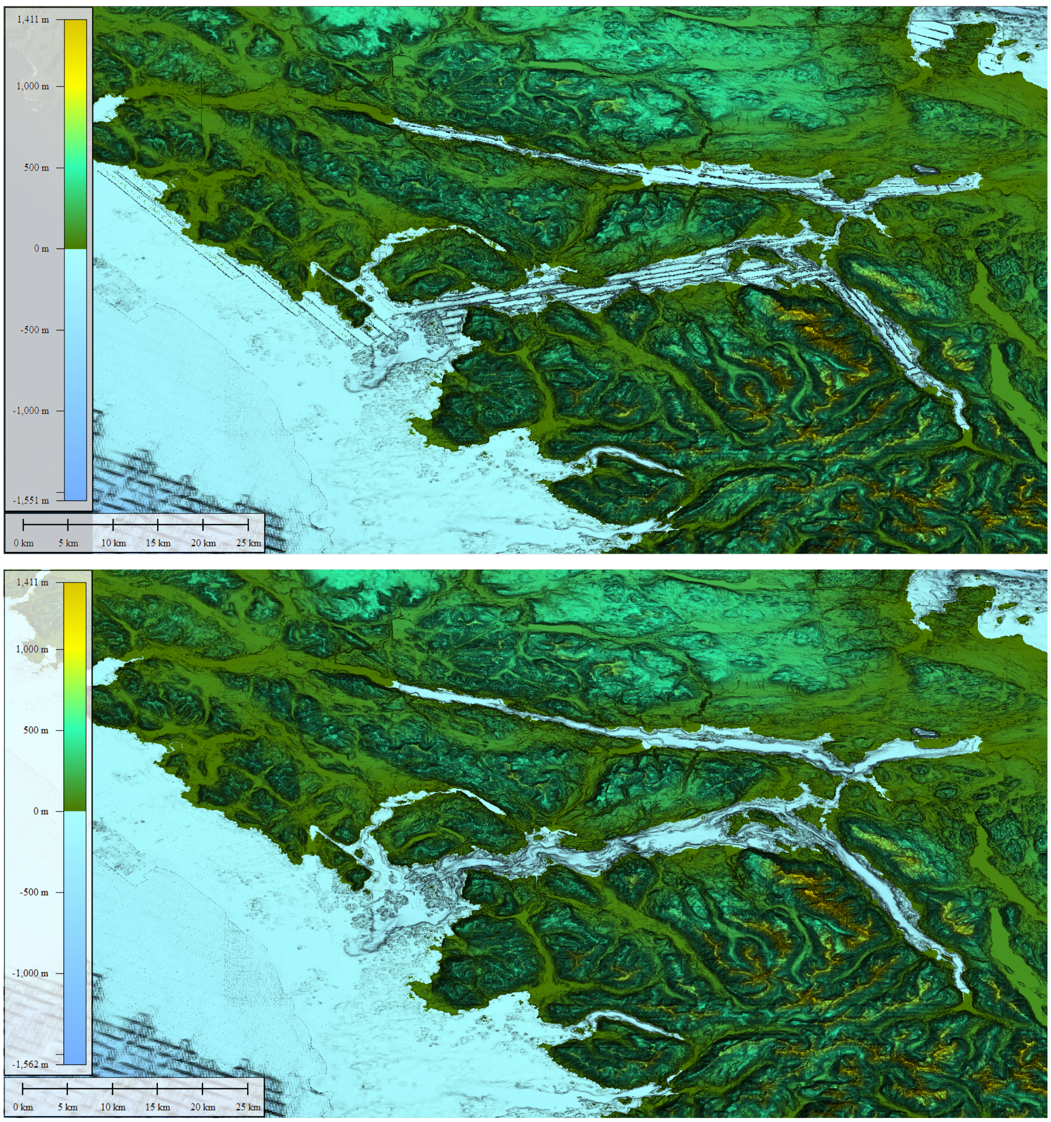


Figure 12. Comparison of the Quatsino DEM before and after removal of misclassified GeoBC LiDAR points. The top image is before alteration and shows significant shallowing of ocean areas throughout, and the bottom image is after alteration.

Some less extensive modifications to McElhanney LiDAR and CHS data were also made based on examination of high resolution data, as well as comparisons with navigational charts and satellite imagery. In addition, it was awkward that the CHS singlebeam points were integrated into the multibeam package that was received. Some of the CHS singlebeam points were deleted from this dataset as they did not match with the co-located modern multibeam. Though these modifications and deletion of erroneous points from the included datasets 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, coastal rivers, and estuaries 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 modelling these evolving coastal zones. While it is possible to collect topographic data using LiDAR at low tide, and bathymetric data by boat at high tide, or commission bathymetric LiDAR that can penetrate shallow depths, the study area of this project is vast and this method of data collection in the intertidal zone was cost prohibitive. Therefore, these intertidal areas of the DEM models may only be an approximation of reality.

Another limitation of the grids is the coordinate system conversions between datasets. The McElhanney LiDAR, GeoBC LiDAR, and TRSI bathymetry, 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 conversion can result in shifts in the data, but is thought to be negligible for this use.

Also, while most of the data was converted to the CGVD2013 vertical datum, some datasets were left in their original datum due to the lower resolution of these datasets. It was decided that converting the datums of these lower resolution datasets would have little to no influence on improving the DEMs and the resulting tsunami models. For example, NOAA's Bathymetric DEM was originally in mean sea level and due to the low resolution of this dataset it was not converted to CGVD2013 and instead left in its original datum.

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.

Finally, in past projects the DEMs underwent a smoothing process on the bathymetric portions under 0m depth. The process smooths out small pockets and rigid features such as artifacts modelled into the DEMs due to interpolation and the stitching together of various data sources. However, it was decided not to apply this process during this project in order to maintain a surface that is truer to the input data.

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.

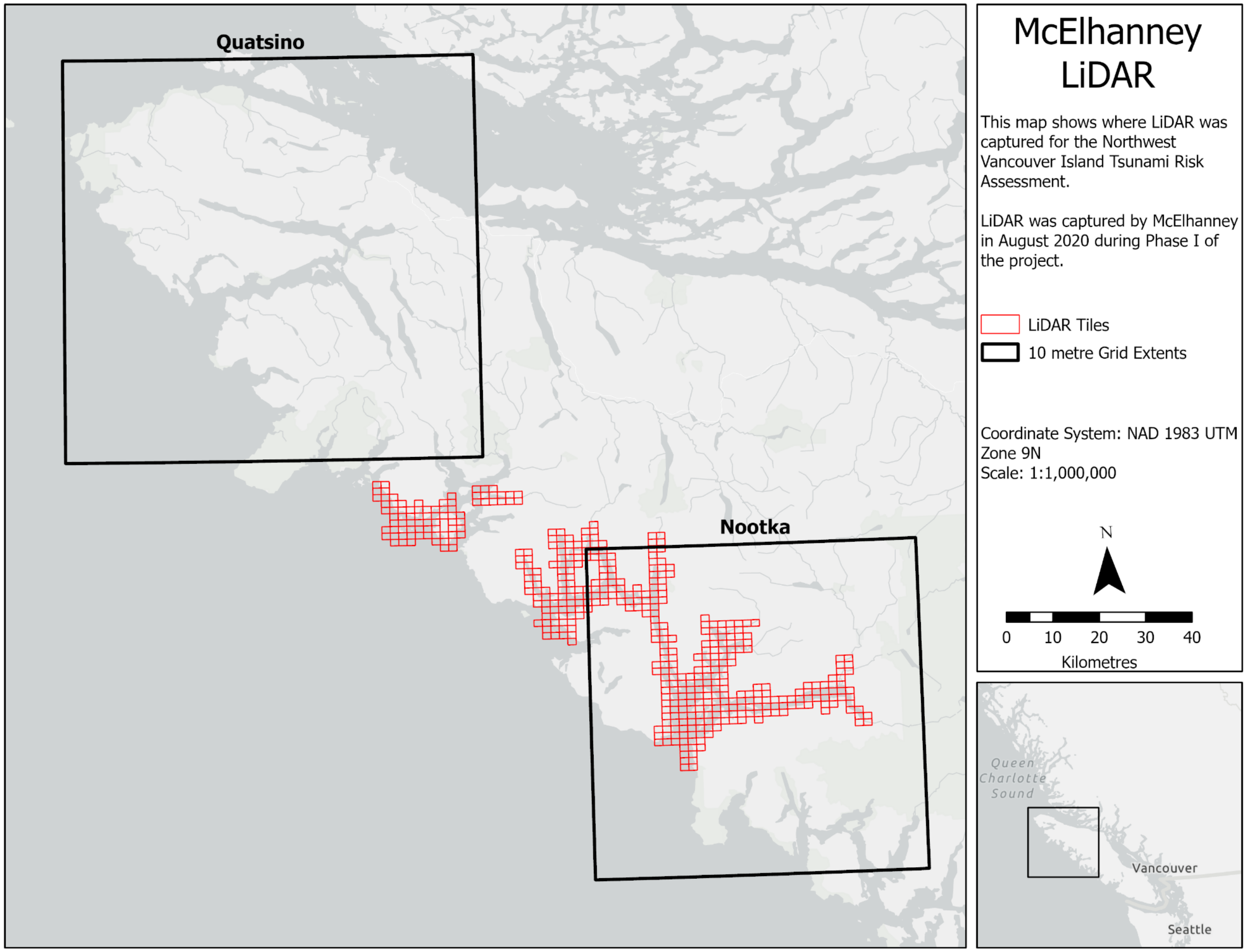

Figure 13. Map of commissioned McElhanney LiDAR extent.

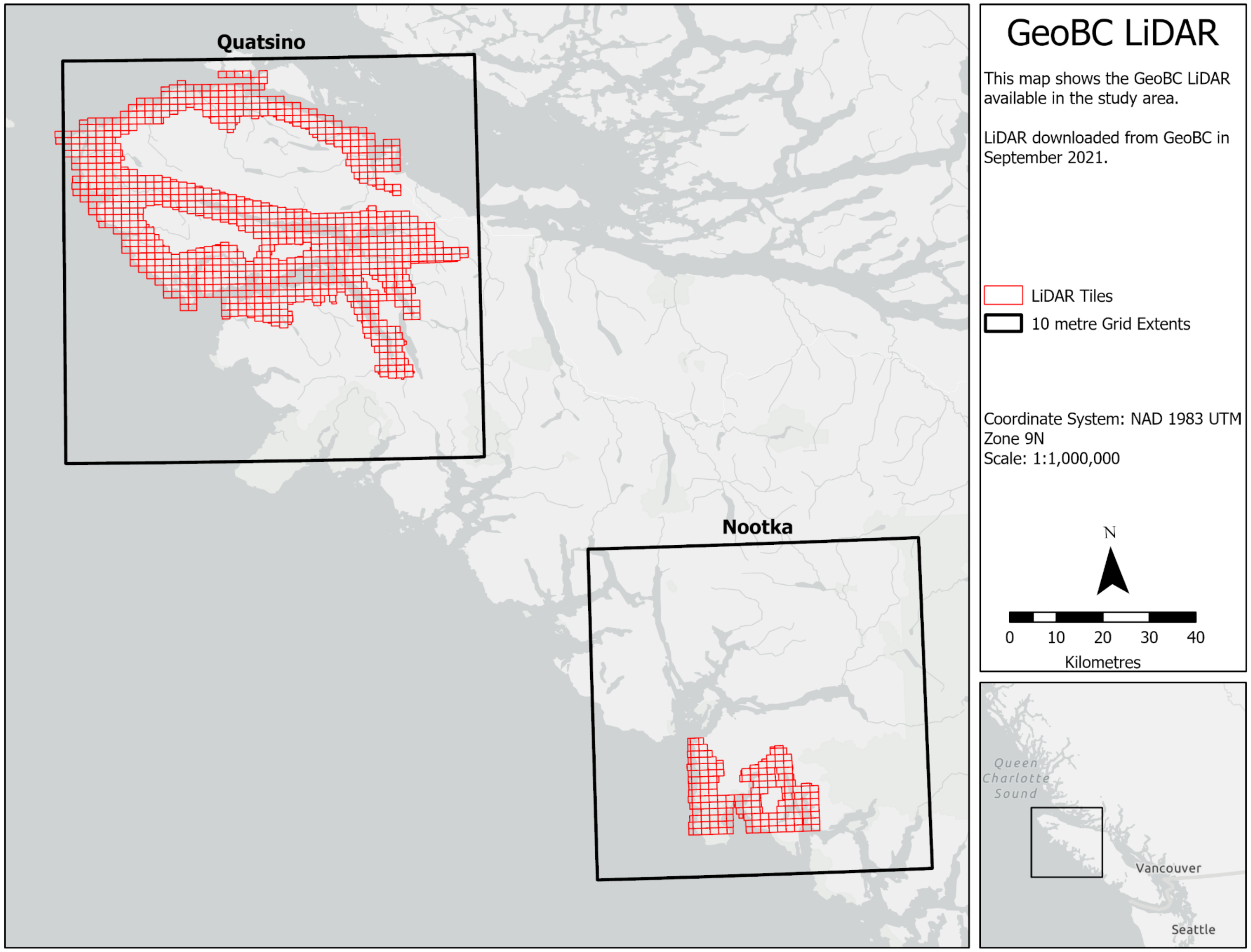

Figure 14. Map of GeoBC LiDAR extent.

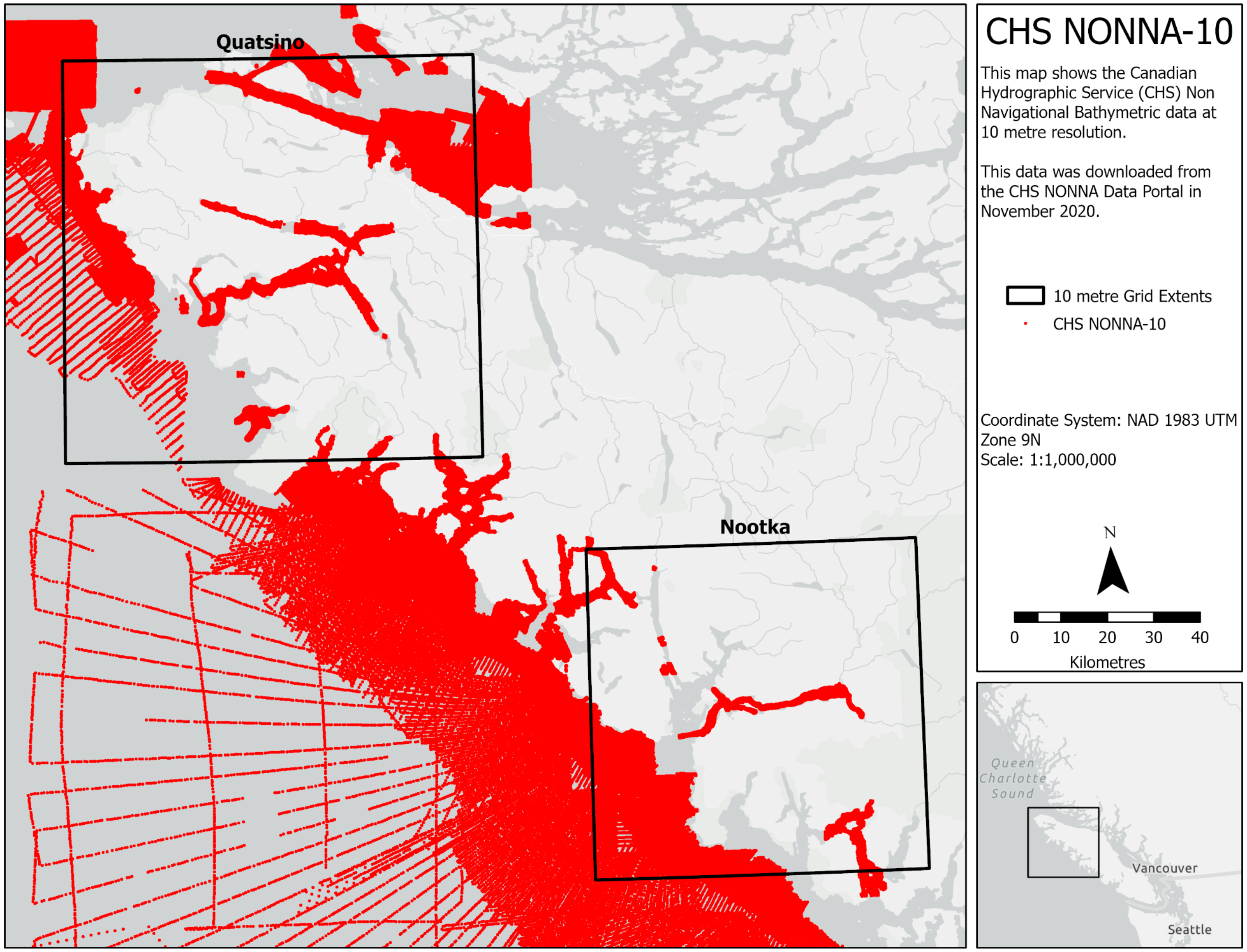

Figure 15. Map of CHS NONNA-10 extent.

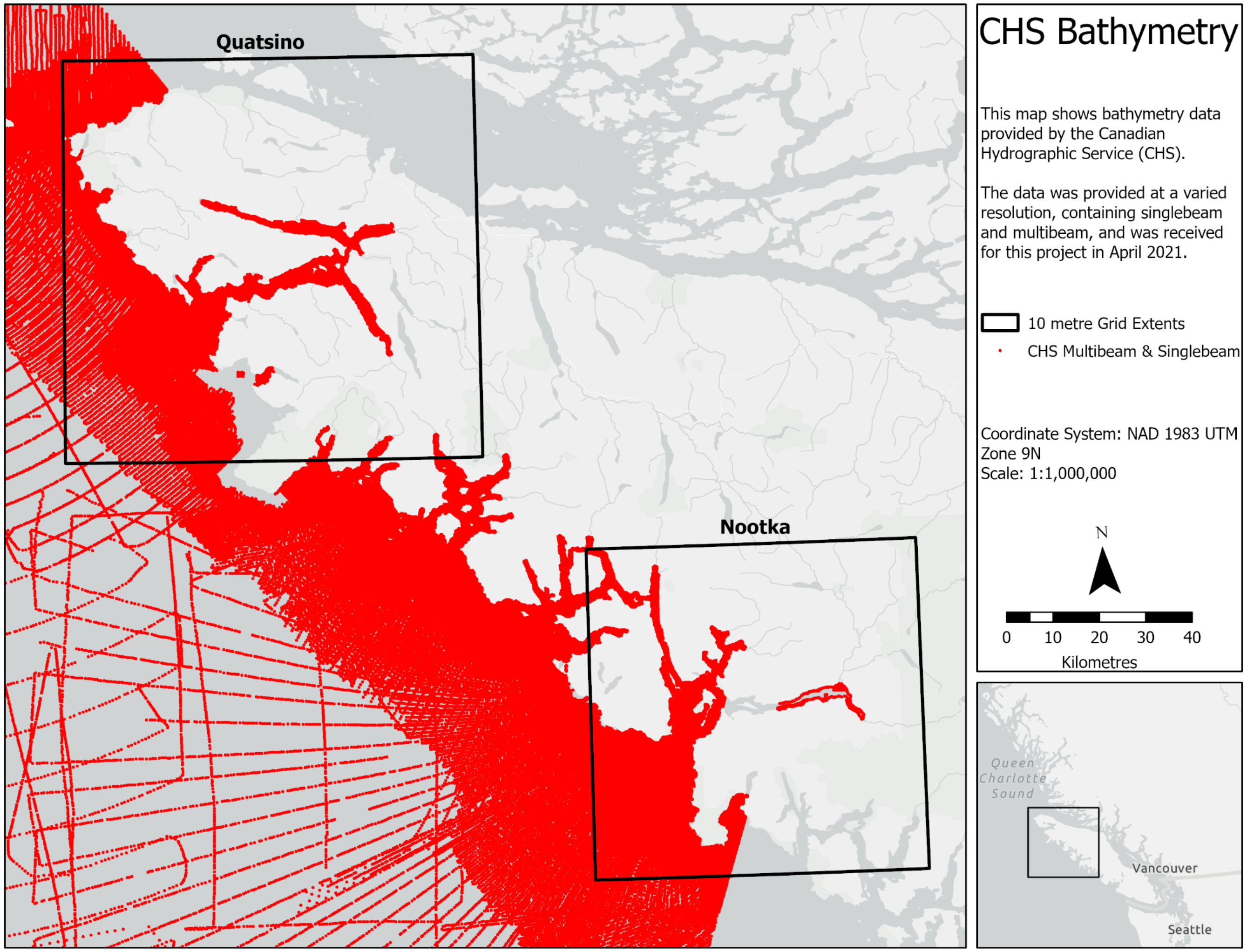

Figure 16. Map of CHS bathymetry extent.

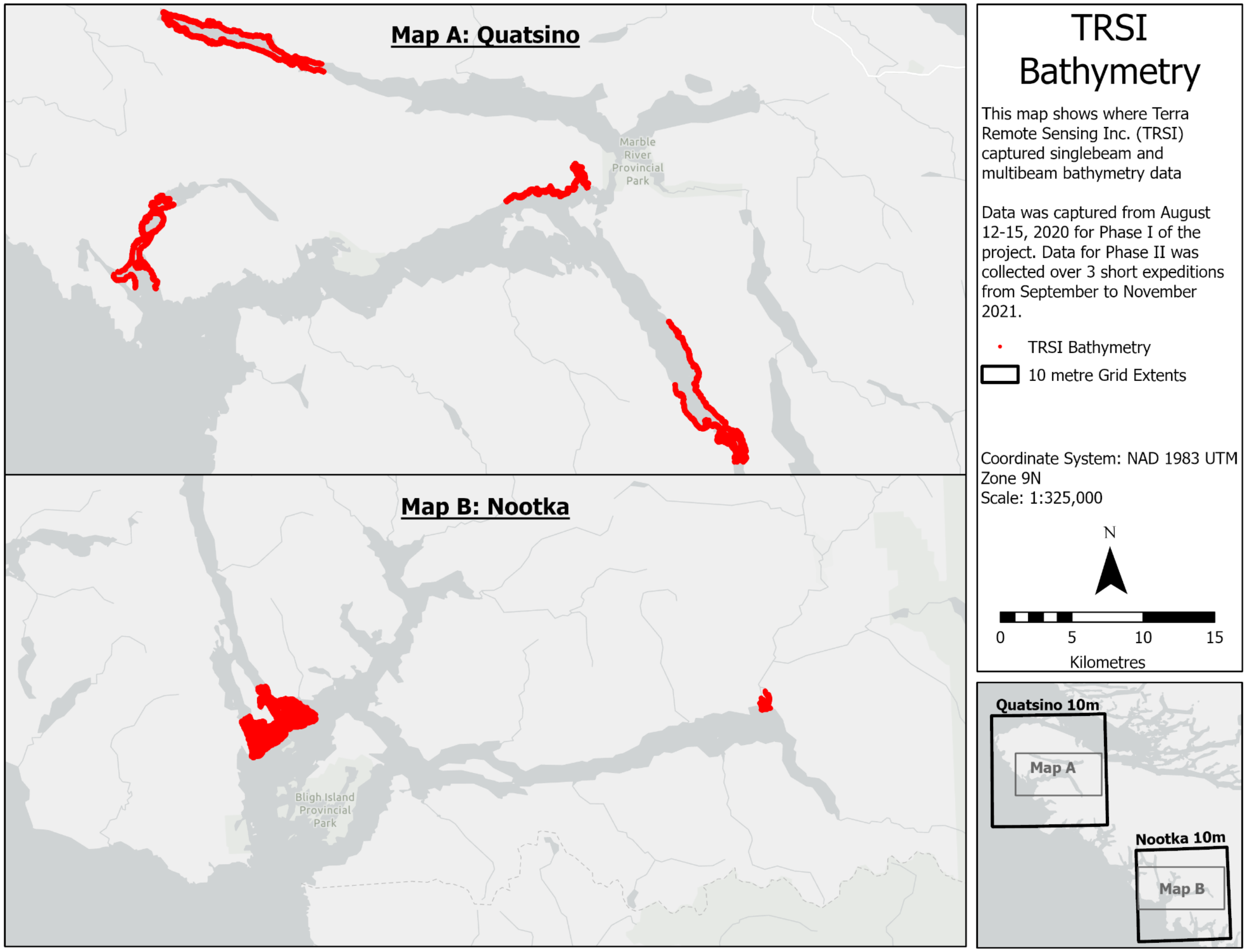

Figure 17. Map of commissioned TRSI bathymetry extent.

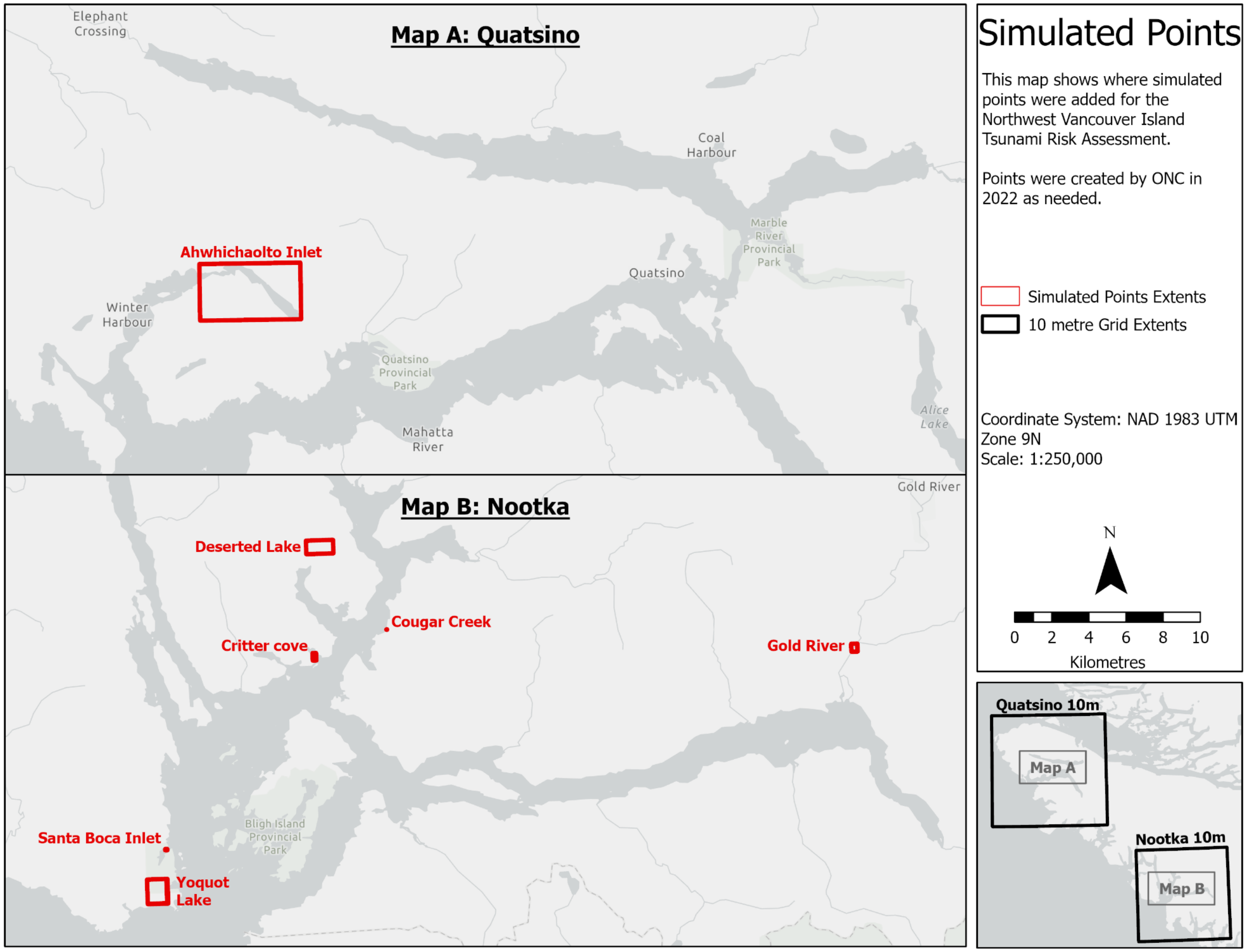

Figure 18. Map of simulated points extents for Quatsino and Nootka 10m grids.