COASTAL DIGITAL ELEVATION MODELS INTEGRATING OCEAN BATHYMETRY AND LAND TOPOGRAPHY FOR MARINE ECOLOGICAL ANALYSES IN PACIFIC CANADIAN WATERS

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2019

Canadian Technical Report of Fisheries and Aquatic Sciences 3321

Fisheries and Oceans Canada   Pêches et Océans Canada

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Canadian Technical Report of Fisheries and Aquatic Sciences

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Cat. No. Fs 97-6/3321E-PDF ISBN 978-0-660-31492-1 ISSN 1488-5379

Correct citation for this publication:

Davies, S.C., Gregr, E. J., Lessard, J., Bartier, P., Wills, P. 2019. Coastal digital elevation models integrating ocean bathymetry and land topography for marine ecological analyses in Pacific Canadian waters. Can. Tech. Rep. Fish. Aquat. Sci. 3321: vi + 38 p.

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ABSTRACT

Davies, S.C., Gregr, E. J., Lessard, J., Bartier, P., Wills, P. 2019. Coastal digital elevation models integrating ocean bathymetry and land topography for marine ecological analyses in Pacific Canadian waters. Can. Tech. Rep. Fish. Aquat. Sci. 3321: vi + 38 p.

We have developed a series of five 20 m coastal digital elevation models (DEMs) for Canada's Pacific region to support spatial analysis, specifically for the nearshore domain, extending from the high intertidal to 50 m depth. Data from the Canadian Hydrographic Service (CHS) and Natural Resources Canada (NRCan) included marine depth soundings and terrestrial elevations, respectively. These data were used to interpolate a continuous 20 m raster extending from depth, across the intertidal, and upland for 5 km from shore. Terrestrial data were incorporated to capture the elevation changes from the marine to terrestrial realms, an important development to support accurate bathymetric derivatives (e.g., slope, roughness) in the nearshore. This new bathymetric product is at a higher resolution and greater extent in shallow waters than previously available DEMs for the area. It provides a critical foundational layer for modelling species, habitats, and environmental variables across Canada's Pacific region and will benefit marine spatial planning initiatives such as Marine Protected Areas and oil spill response strategies.

RÉSUMÉ

Davies, S.C., Gregr, E. J., Lessard, J., Bartier, P., Wills, P. 2019. Coastal digital elevation models integrating ocean bathymetry and land topography for marine ecological analyses in Pacific Canadian waters. Can. Tech. Rep. Fish. Aquat. Sci. 3321: vi + 38 p.

Nous avons développé une série de cinq modèles numérique d'élévation bathymétrique à une résolution de 20 m a été développé pour la région du Pacifique pour supporter des analyses spatiales, spécifiquement pour la côte, de l'intertidal jusqu'à 50 m de profondeur. Des données de profondeurs marines et d'élévations terrestres sont provenues du Service Hydrographique du Canada et des Ressources Naturelle du Canada. Ces données ont été utilisées pour interpoler un raster continue d'une résolution de 20 m entre les eaux profondes (plus de 50 m), à travers l'intertidal, jusqu'à 5 km du côté terrestre. Les données terrestres ont été incorporée pour capturer les changements d'élévation entre les zones marines et terrestres, un développement important pour la précision des dérivatives calculées (ex. pente, rugosité, etc.) à partir de ce model et essentielle pour les études de la côte. Ce nouveau produit bathymétrique est à une meilleure résolution et à une ampleur plus grande dans les eaux peu profondes que les modèles disponible précédemment. Ce modèle fournie une couche de fondation essentielle pour la modélisation des espèces, habitats ou certaines variables environnementales à la grandeur de la côte du Pacifique Canadien. Ces efforts vont contribué à des initiatives de planification spatiale en cours tel que les aires protégées et les stratégies pour des réponses d'urgence à des déversements d'huile.

INTRODUCTION

There is a growing need to identify and map different types of habitats and biological communities to support marine spatial planning initiatives in Canada's Pacific region, and bathymetry, or the underwater topography of the ocean floor, is a critical component. For the nearshore, defined here as the intertidal areas and shallow waters from the high water line to depths of 50 m, the resolution of the bathymetry needs to be well resolved to successfully map nearshore habitats, as this zone is highly variable.

Bathymetric digital elevation models (DEMs) are continuous representations of the seafloor that are derived from depth measurements and are stored in a raster data format, with each cell representing the average depth of the area contained within that cell (Amante and Eakins 2016). Previously available raster bathymetry data are of limited utility in the nearshore region because of either coarse resolution or incomplete spatial extents. The 500 m (Finney 2010) and 100 m (Gregr 2012) resolutions are too coarse to represent important depth changes in some locations along the coastline. This report describes the creation of a series of 20 m coastal DEMs for Canada's Pacific region to fill this gap.

The mapping of the B.C. coast has a long history. It began with Russian fur traders in the early 1700s. This was followed by Spanish and British expeditions in the 1770s (Library and Archives Canada 2018). The first detailed chart was produced by Captain George Vancouver in 1798 for the Royal Navy (Archer 1987). These early explorers measured depth by sinking a weighted line and measuring its length. Positioning was typically done using ship-based sextant to measure angles to prominent shore-based features or stars. Horizontal positional accuracy and imprecise line depth soundings resulted in mapping errors and low-resolution interpretations of topography (Finkl and Makowski 2016). Depth measuring technology progressed to early acoustic methods in the early 20th century (Dierssen and Theberge Jr 2014). In these single beam acoustic measurements, sound is propagated into the water from a transducer, reflected from the seafloor, and its arrival time recorded at the point of origin (Monahan 2009). The bottom depth is based on the length of time for the sound pulse to return to the source using an assumed water temperature. Advances in depth sounding technology from single beam to large, multi-transducer arrays, or multibeam echo sounders (MBES), allow for a large swath of area to be surveyed at once.

MBES surveys have provided high resolution data for many areas along the coast and continue to be a priority for the Canadian Hydrographic Service (CHS). However, there are logistic challenges to applying this technology to areas shallower than 50 m, or the nearshore region. This region cannot be easily accessed by larger vessels and is therefore often omitted from MBES surveys. In addition, the MBES acoustic swath becomes narrower in shallower water. Thus, nearshore surveys take longer to attain 100% bottom coverage because of slower speeds, increased ping rates and data volume, coastal complexity, and narrower footprint.

Bathymetric data collected by the CHS over the past 100 years includes a range of methods from weighted-line to MBES (Canadian Hydrographic Service 2017). These field data were compiled into survey documents that ranged from hand-inked, linen-backed field sheets to multi-terabyte MBES digital data. Survey documents are compiled by cartographers to produce nautical charts.

CHS digital charts are available and have been used for nearshore modelling (Gregr et al. 2013). While these vector data may represent the nearshore bathymetry of the B.C. coast more accurately than available raster data, their utility for spatial analysis is limited as they cannot be used to calculate bathymetric derivatives (e.g., slope, rugosity) commonly used as predictors in habitat suitability models. An additional problem with digital charts is that they reflect the resolution of their paper counterparts. This can create seams between adjacent charts of different resolutions when they are mosaicked together for use in spatial analysis over larger areas.

The provision of CHS digital data to analysts, modellers, and the GIS community has evolved over the last 15 years into a collaborative venture. The recent availability of the CHS bathymetric single beam point data from field sheets and MBES provided an opportunity to produce a consistent high resolution raster for nearshore waters. Our methodology incorporated terrestrial elevations to preserve the shoreline details and provide a consistent resolution for the entire Pacific Canadian coast with the ability to calculate accurate bathymetric derivatives. The final series of 20 m DEMs better represents the intricacies of our shoreline and can support analytical work of the nearshore region, specifically from the 0 – 50 m depth range.

METHODS

OVERVIEW

We integrated the depth soundings from CHS field sheets and available MBES surveys with a high water tide line and terrestrial elevations from Natural Resources Canada (NRCan) to create a series of 20 m DEMs of the coastal area of Pacific Canada (data sources are described below). We used the natural neighbour algorithm (ESRI 2017) to interpolate depths at unsampled sites using data from point observations within the same region (Li and Heap 2008). The high water line was used as a reference to accurately bound the nearshore region and allow the DEM to be extended across the intertidal region. Upland areas were included to support the accurate calculation of terrain descriptors. All marine depths below a height of 0 m were presented as positive and all terrestrial elevations above a height of 0 m were presented as negative. The final product is a series of DEMs that cover the British Columbia coast.

All spatial analysis was performed in ArcMap ESRI 10.2.2, or greater, using the Spatial Analyst extension (ESRI 2014). Additional data preparation was completed using the Geospatial Modelling Environment (Beyer 2012) and the R Statistical Software (R Development Core Team 2013).

STUDY AREA

The series of 20 m DEMs was developed for the coastal area of Pacific Canada. The study area was divided into five regions (Fig. 1) to facilitate data management and computation: Strait of Georgia (SoG), Queen Charlotte Strait (QCS), North Central Coast (NCC), Haida Gwaii (HG), and West Coast Vancouver Island (WCVI). Data were compiled and analysed for each region separately. In some cases, due to the large number of input points, regions were further broken down into smaller areas for parts of the analysis.

The series of 20 m DEMs were developed over several years during a period where the quantity and quality of the available data was rapidly increasing as CHS consolidated and reviewed its data holdings. As a result, there are some regional differences in methodology that either took advantage of additional data, or needed to compensate for data that were not available. These differences are outlined in the sections below.

DATA SOURCES

The data used to build the series of 20 m DEMs were acquired from CHS, Natural Resources Canada (NRCan), and the National Oceanic and Atmosphere Administration (NOAA). All data included positional locations and depths (or elevations for terrestrial positions) and came in one of the following four formats: points, polyline, polygon, or raster (Table 1).

Table 1: Data used to build the 20 m DEM (source data are cited in the following sections where discussed)

Dataset	Description	Format	Source[1]	Regions used[2]
Pacific High Water Line	A high resolution vector coastline that represents the Higher High Water Large Tide mark in B.C.'s tidal waters	Polyline shapefile	CHS	All regions
Field sheets	Depth soundings recorded on spatial field notes (i.e., field sheets) collected using a number of different methods including lead-line and single beam echo sounders	Point shapefile	CHS	All regions
B.C. Coast Soundings	Additional depth soundings used in digital charts	Point feature class within the Geobase geodatabase	CHS	All regions
B.C. Coast Rocks	Elevations of pinnacles, rocks, and rocks awash	Point feature class within the Geobase geodatabase	CHS	All regions
S-57 Vector digital charts	Additional depth soundings used in digital charts	Point feature class within the Series 57 (S-57) geodatabase	CHS	QCS, NCC, HG, WCVI
CHS Intertidal polygon	Polygon outlining the intertidal region between the higher high water line and the lower low water line	Polygon shapefile	CHS	HG, WCVI
Multibeam	A regularly spaced array of depth values collected with a swath system of multiple sonars	Raster	CHS	SoG, NCC, HG
Tide height	Tidal height observations from various tide stations and lighthouses	Comma delimited file	CHS	All regions
NOAA depth soundings	Depth soundings collected by NOAA	Point shapefile	NOAA	HG
Canadian Digital Elevation Data	A regularly spaced array of terrestrial elevations referenced to a common vertical datum	Raster	NRCan	All regions

1: CHS = Canadian Hydrographic Service, NOAA = National Oceanic and Atmosphere Administration, NRCan = Natural Resources Canada
2: Strait of Georgia (SoG), Queen Charlotte Strait (QCS), North Central Coast (NCC), Haida Gwaii (HG), and West Coast Vancouver Island (WCVI)

TIDE HEIGHT CORRECTIONS

We used high water elevations at various tidal stations and lighthouses across the study area to adjust the reference depth (i.e., datum) for the regional DEMs, to improve the correspondence of the marine and terrestrial elevations. Tide height corrections for each region were calculated from historic daily high tide heights from local tide stations (Table 2) (Canadian Hydrographic Service 2014). Daily high tide heights from at least two tide stations were used to calculate mean high tide correction for most regions. Time periods varied by tide station, but usually corresponded to the first year through the most recent year of available data. For Queen Charlotte Strait only one tide station was available, and for Haida Gwaii 30 tide stations were used over a shorter time frame. The corrected high tide height was used to estimate the elevation of the high water tide line and the terrestrial elevations data (see Data Preparation for details).

Table 2: Tide Stations and Corrected High Tide Heights for each Region

Region	Tide Station	Years	Mean High Tide Height (m)	Corrected High Tide Height (m)
Strait of Georgia	Point Aktinson	1914; 2011	3.11	3.01
	Campbell River	1965; 2011	2.91	
Queen Charlotte Strait	Port Hardy	1964; 2012	2.88	2.88
West Coast Vancouver Island	Winter Harbour	1963; 2002	2.21	2.14
	Tofino	1905; 2002	2.06	
North Central Coast	Bella Bella	1906; 2013	2.82	3.37
	Prince Rupert	1909; 2013	3.80	
Haida Gwaii	30 tide stations	1990 - 2004	2.81	2.81

DATA PREPARATION

High Water Line

The CHS Pacific High Water Line shapefile (Table 1) was used as the boundary between the marine and terrestrial domains. The high water line is a high resolution vector coastline representing the Highest High Water Large Tides mark in B.C.'s tidal waters (Canadian Hydrographic Service 2017).

The shapefile was clipped to the boundaries of each of the five regions. Points were created every 10 m for use in the interpolation. Although the high water line did contain some elevation values, they were inconsistent and at some locations were known to be grossly inaccurate. Instead, the depth assigned to these points was calculated from historic daily high tide heights from local tide stations (Table 2). The calculated tide height was negated to reflect height above chart datum and assigned to the high water line points for the entire region.

For West Coast Vancouver Island and Haida Gwaii the CHS intertidal polygon (Table 1) was integrated into the raster development by separating it into high and low water polyline shapefiles, and creating points every 10 m. Values for low water line points were set to 0 m to reflect chart datum. For West Coast Vancouver Island, the corrected high tide height (Table 2) was used for the high water points. For Haida Gwaii, the high water line values were taken from an older 2006 version of the CHS high water line, which included elevation values, instead of the corrected high tide heights.

Terrestrial Data

Terrestrial points were compiled from NRCan Canadian Digital Elevation Data (CDED) raster tiles, CHS high water points, and B.C. Coast Rocks points feature class (Table 1).

The series of 20 m DEMs was extended 5 km inland to allow changes in elevations throughout the intertidal region to be characterized accurately. Terrestrial data ensured the interpolation across the high water line accurately captured coastal features such as estuaries and other low-lying areas. The CDED raster tiles were downloaded from a public NRCan website. Tiling allows a large raster dataset, such as a countrywide elevation model, to be divided into manageable pieces. The set of 20 m raster tiles consist of an ordered array of ground or reflective surface elevations, recorded in metres at a scale of 1:250,000 (Natural Resources Canada 2017). Tiles along the Pacific coast used in this analysis were validated between 1981 and 2011 (Natural Resources Canada 2013).

For each region, CDED tiles were mosaicked using the Blend setting on the ArcGIS Mosaic tool. The resulting raster was then clipped to include only the area within a 5 km buffer from the CHS high water line. Areas of water were then removed using the Raster Calculator and a water mask. The CDED rasters use the mean tide height to reference elevations as opposed to the CHS data which use low tide height as a reference. Elevation values were adjusted by adding the corrected tide height calculated in Table 2. Terrestrial elevations in Haida Gwaii had an additional correction of 1.2 m subtracted because comparison of these elevation values with 1:20,000 provincial Terrain Resource and Inventory Mapping data showed that the terrestrial elevations were consistently too high. Once elevation values were corrected, the rasters were converted to points at 20 m resolution and their elevation values were negated. The B.C. Rocks points feature class and the high water line points were merged with the CDED points to create the terrestrial data (Fig. 2).

Marine Data

Marine points (Fig. 3) were gathered from all available CHS field sheet soundings, NOAA soundings, soundings and rock features from the S-57 and Geobase geodatabases, MBES soundings, and the high water line points for the region (Table 1). Field sheets were provided in the form of point shapefiles. The S-57 and Geobase datasets contained additional depth soundings extracted from digital vector charts. MBES rasters had spatial resolutions between 2 and 10 m.

The point distribution and spatial extents of the field sheet data varied across surveys according to the topographical complexity and navigational needs at any given location. In areas where high resolution information about seafloor depths is necessary for navigation, such as near harbours or known hazards to navigation, there are more points and these points are closer together (< 20 m apart). Point densities are also higher around populated regions and at locations with a high amount of vessel traffic. In other locations, such as the middle of the Queen Charlotte Strait, points are more dispersed (> 20 m) (Fig. 4). Over the entire Queen Charlotte Strait region the variation in point densities over 1 x 1 km grid can be seen in Figure 5, this variation in coverage for the marine points was observed in all regions.

Appendix A outlines the number of points compiled for each of the five regions. The field sheets were the primary data source, but were supplemented where necessary using MBES data to fill large gaps in coverage. When used, high resolution MBES data were converted into points that matched the resolution of the MBES and these points were then subsampled to a resolution consistent with the field sheet point distribution in neighbouring areas. If not resampled in this way, the MBES data generated artefacts around the edges in DEM derivative products (e.g., slope). As these derivatives are important for many applications of the DEM, considering how combining different data affects these derivatives is critical.

INTERPOLATION

Interpolation is commonly applied to build a continuous surface from a collection of points with associated depths, as it is logistically unfeasible to collect evenly spaced depth soundings at 20 m horizontal resolution across large spatial extents. Interpolation is the mathematical process of predicting unknown values from other measurements made at point locations within the same area (Burrough and McDonnell 1998). DEMs can be created through variety of interpolation techniques, all of which share the assumption that bathymetry is spatially autocorrelated (Amante and Eakins 2016). This assumption allows new data points to be estimated based on the values of nearby points.

Calculating new point values involves defining the neighbourhood of points to use in the prediction and choosing the appropriate mathematical function to represent the variation over this neighbourhood. The chosen interpolation technique should be based on measurement uncertainty, sample density, sample distribution, terrain characteristics, and computational resources (Amante and Eakins 2016). The appropriate interpolation algorithm will also depend on the anticipated use of the resulting surface and whether or not it is acceptable to extrapolate beyond the range of input values.

Interpolation techniques can be classified based on the assumptions and characteristics used to estimate the depths of unknown areas surrounding known measurements (Amante and Eakins 2016). The amount of data used to interpolate new points can either be global, which uses all the sampling point data in the study area to make feature fitting for the region, or local, which simply uses the neighbouring data points to estimate the unknown point value (Tan and Xu 2014). Interpolation techniques are either deterministic or geostatistical; deterministic techniques create surfaces based on mathematical formulas, while geostatistical techniques are based on statistics and also include some measure of the accuracy of predictions (Childs 2004). How the interpolation method handles the input points can also be categorized as exact or inexact; depending on whether it is desirable for the resulting surface to preserve the input data values (Burrough and McDonnell 1998). The main difference between interpolation methods is the neighbourhood size or number of points used for each interpolated value, and the weighting (or influence) given to each of these points. These methodological differences make each algorithm suited to different spatial distributions of input points and different applications (Table 3).

The data available to build the 20 m DEM was distributed unevenly across the study area and consisted of continuous depth or elevation values. The topography in Pacific Canada is extremely variable and includes steep fjords, many small archipelagos, and broad beaches. After considering several interpolation techniques (Table 3), we selected natural neighbour interpolation because it best suited our large data of unevenly distributed points. Natural neighbor uses a local neighborhood of points to interpolate new values and this neighbourhood size will vary depending on the proximity of surrounding points. It is a deterministic and exact interpolation method, therefore the values of the original data points are preserved and represented in the final DEM. Natural neighbour interpolation obtains the closest subset of input points to an unknown point, and applies proportionate area weights to the subset in order to interpolate the value of a new point (Garnero and Godone 2013, Sibson 1981). The number of given points used for the computation at each new point is variable, depending on the spatial configuration of data points (Mitas and Mitasova 2005). This allows the natural neighbour method to efficiently handle large input point data with clustered scatter points (Childs 2004). Natural neighbour also did not require validation of the available coastline (i.e., barriers) file, which on cursory inspection contained many unclosed polygons. A topologically correct polygon layer is necessary to apply any interpolation method using barriers.

The interpolation begins with a set of input points (Fig. 6A); a polygon is created for each input point such that the edges and vertices of each polygon are equidistant from two or more points (Fig. 6B, (Boots 2005)). These Thiessen polygons (also called Voronoi polygons) divide a region up in a way that is determined by the configuration of the data points, with one observation per polygon (Burrough and McDonnell 1998). To create a new continuous grid, new points are overlaid on the Thiessen polygons. The natural neighbours of any new point are determined by the number of neighbouring polygons and the area of overlap for each neighbouring polygon (Fig. 7). The values of the new points are calculated based on the proportional contribution of each of the neighbouring polygons.

Table 3: Comparison of interpolation methods (mostly modified from Li and Heap (2008) and Burrough and McDonnell (1998)

Method	Deterministic/ geostatistical	Local/ global	Exact/ inexact	Computing load	Assumptions	Limitations	Best for
Inverse distance weight (IDW)	Deterministic	Local	Inexact	Small computer resources	The weight of a sampled data value is inversely proportional to its distance from the estimated value.	Neighbourhood size (number of points) used is determined by the user. Finding the appropriate neighbourhood size requires knowledge of the dataset. Poor choice of neighbourhood size can give artefacts when used with high point densities. No error assessment.	The specified search radius (neighbourhood size) of IDW is best suited with uniformly dispersed data.
Nearest neighbour	Deterministic	Local	Exact	Small computer resources	Best local predictor is nearest point.	Output tessellation pattern depends on the distribution of the input data. No error assessment.	Performs best with categorical data (e.g. land-use classification). Can produce blocky results with continuous data because there is no area-based weighting.
Natural neighbour	Deterministic	Local	Exact	Small computer resources	Best local predictor is data points in the surrounding polygons.	No error assessment.	The variable neighbourhood size gives this algorithm the flexibility to handle unevenly distributed and large data.
Spline with barriers	Geostatistical	Local	Exact	Moderate computing power	Estimates new values using a mathematical function that minimizes overall surface curvature taking into account the impact of a physical barrier on the spatial correlation of two points. Can make estimates outside the range of input points.	Extreme changes in elevation, such as cliff faces are not represented well by the smooth-curving surface. Neighbourhood size and weight value are defined by the user; higher values for these parameters produce a smoother output surface. Requires well structured data on the spatial barriers.	Useful to interpolate environmental variables where the spatial correlation will be impacted by physical boundaries Small areas at high resolution or large extents at low resolution.
Kriging	Geostatistical	Local with global variograms	Exact	Moderate computing power	Geostatistical methods are used to incorporate both the distance and the degree of variation between known data points for prediction.	Requires care when specifying how modelling parameters describe spatial variation of the input dataset.	When data and computational resources are sufficient to compute variograms, kriging provides a good interpolator for sparse data.

DEM DEVELOPMENT

As described above, the input data were grouped into two point layers; marine points included those along and below the high water line, while terrestrial points included points along and above the high water line. Point data from field sheets that overlapped two regions was included in the interpolation of both regions to support continuity between the five regions. All depths below chart datum were denoted as positive while elevations above chart datum were denoted as negative. The depth range, sign, and projection of input points were verified in ArcMap for quality control before the analysis. Duplicate points were removed from the input data. Raster origin and size were defined at the beginning of the analysis to anchor all five raster layers to the same raster grid and ensure that the boundaries for each region align.

The ArcGIS Natural Neighbour interpolation tool was run on separate terrestrial and marine input datasets for each region (Figs. 2 and 3). Both interpolations assigned invalid values in the resulting rasters to some portions of the opposite domain (e.g., artefacts were created in the terrestrial interpolation where it assigned values to grid cells representing channels and fjords, while the marine interpolation assigned values to peninsulas and small islets; Figs. 8, 9). We used the Raster Calculator tool to remove marine cells from the interpolated terrestrial raster using a marine mask based on the high water line (Fig. 10). Using the inverse operation in Raster Calculator and the same marine mask the terrestrial cells from the interpolated marine raster were also removed (Fig. 11). The marine and terrestrial layers were then merged in Raster Calculator to create the final 20 m resolution bathymetry layer (Fig. 12 and Appendix B).

Edge-effects were created along the edge of the bounding box, where the neighbourhood of points for interpolation was smaller. These edge effects were removed using a raster mask.

QUALITY CONTROL

In their review of various interpolation techniques, Amante and Eakins (2016) demonstrate that accuracy is decreased (i) at lower cell sampling densities, (ii) as the distance to the nearest measurement increases, and (iii) in areas of high slope and curvature. These are an important considerations when evaluating the accuracy of the 20 m DEM, particularly in both deeper waters with limited depth soundings and in areas with high topographic variation.

The quality of GIS products is often judged by the visual appearance of the end-product on the computer screen (Burrough and McDonnell 1998). A visual inspection was thus the first step in evaluating the results of the spatial analysis. Visible anomalies included blocky or bumpy areas implying some groups of input points had either an inappropriate tide height correction, or the wrong sign (negative as opposed to positive). Once identified, these anomalies were corrected and the interpolation was rerun. Visual inspection also verified the cell alignment between marine and terrestrial interpolation outputs and between neighbouring regions.

Further visual quality assessment was applied using bathymetric derivatives obtained from the ArcGIS Spatial Analyst Toolbar and the Benthic Terrain Model Tool (Walbridge et al. 2018). In some locations, these derivatives were better able to identify inconsistencies in the input data than the original DEM by illustrating the rate of change across raster cells. The terrain characteristics that proved to be the most useful for identifying anomalies were the standard deviation of the slope and the bathymetric position index (BPI). The standard deviation of the slope measures the rate of change and direction of the slope. BPI assesses the change in slope by finding the difference between the elevation value and the mean elevation of all cells in a defined ring surrounding the location and is used to identify seafloor features such as canyons and ridges (Walbridge et al. 2018).

The anomalies found using these derivatives were due to either areas of high topographic variation, or locations where two sources of input data did not have similar values. Where obvious data errors were found, the input data were assessed and removed if the depth soundings were well outside the neighbourhood values. Where possible, new input points were added to these areas from MBES or other sources and the analysis rerun. At other locations the factors contributing to the anomalies were noted as limitations (see below).

The bathymetry layer was converted into a polygon layer using depth categories (Table 4) for use in other analyses (e.g., Gregr et al. 2013). This provided an opportunity to validate the horizontal dimension of the 20 m DEMs and assess how smooth the progression from the intertidal to deeper depths in the nearshore region was. For most locations, in the visual assessment the CHS High Water Line corresponded with the location of the intertidal depth category of the polygon layer, which suggests that the values assigned to the CHS High Water Line corresponded well with the surrounding marine depths and terrestrial elevations.

Table 4: Depth categories used to visually inspect the 20 m DEM

Depth Category	Depth Range (m)
1	-5 to 0 (Intertidal zone)
2	0 to 5
3	5 to 10
4	10 to 20
5	20 to 50

LIMITATIONS

The accuracy of any given grid cell in the series of 20 m DEMs depends on the local source data density and their accuracy, as well as on how accurately the natural neighbour interpolation can capture the underlying autocorrelation. This will be based on the agreement between the interpolated values and the surrounding known values (Amante and Eakins 2016). In other words, how smooth or blocky the interpolated surface appears during a visual inspection of the layer. It is usually assumed that such disagreements identify locations of poor data quality or density, or where the interpolation algorithm was not appropriate for either the input data or the goal of the analysis. But this is not necessarily the case. Some anomalies may not be resolvable in locations where the data density is too sparse, or the topography is too complex. If the reasons for disagreement between model results and ground-truthing data can be identified, they can be documented as sources of errors and uncertainties for users of the coastal DEMs. Knowledge of how such errors are produced and propagated can improve our understanding of spatial patterns and processes (Burrough and McDonnell 1998).

Some areas along the Pacific Canadian coast are misrepresented in the 20 m DEMs either due to the distribution of the input points, scale of the output, or challenges associated with the interpolation method. Areas of common misrepresentation include deeper waters in the middle of channels, locations of limited interest for navigational safety where data are sparse, and along steep shorelines. Such localized imperfections in the series of 20 m DEMs resulted from three factors: complex topography, vertical inaccuracy at the high water line, and limited data points. Users of the 20 m DEMs should be aware of these limitations and spend time exploring how these anomalies may impact their analysis, the creation of mosaicked data, and bathymetric derivatives. In addition, users of the 20 m DEMs should be cognizant that all marine depths below 0 m are positive and all terrestrial elevations above 0 m are negative. Positive depth values allow for ease of use in most marine spatial analysis applications. However, for some applications such as calculating BPI using the Benthic Terrain Model Tool marine depths are assumed to be negative and it may be necessary to invert these values.

COMPLEX TOPOGRAPHY AT THE SHORELINE

The complex shoreline topography in Pacific Canada can be difficult to represent, even at high resolutions. For example, steep fjords with cliff features that extend from the terrestrial region deep into the marine region can change in elevation dramatically across 20 m. Such features – where the vertical change is several times the horizontal resolution – cannot be precisely captured using our 20 m DEM. Instead, neighbouring grid cells that would represent a continuous elevation change across a horizontal plane will instead appear fragmented and blocky due to the large variation in cliff depth values (Fig. 13).

VERTICAL INACCURACY AT THE HIGH WATER LINE

An appropriate high water line would include accurate elevations. The CHS high water line, while accurate in the horizontal component did not have suitable elevation values throughout the study area. To correct for this a calculated high tide height was assigned to all high water line points within each region. In some locations, the corrected high tide height was either too high or too low. These inaccurate heights may lead to an incorrect discontinuity at the high water line. Because the high water line is used to bound both the intertidal zone and the upland areas, the calculated high tidal height may not agree with the local depth soundings or terrestrial elevations, creating localized artefacts when interpolated with the surrounding marine and terrestrial points. These artefacts can manifest as either a large height step between the high water line and the closest marine depth values when the high water line height is too high, or as inundated land areas when the high water line height is too low. Visual inspection of the 20 m DEMs with the high water line showed that this anomaly occurred more often at locations with limited depth soundings and far away from tide stations, suggesting that the distance between a tide station and a point of interpolation can impact the accuracy of the DEM. This phenomenon is not entirely unexpected given the knowledge that tide table accuracy also decreases with distance from the nearest tide station. Future coastal DEMs could include chart tidal information, or where available more tide station data to assign more accurate values to the high water line throughout the B.C. coast.

DATA DENSITY

In remote locations along the coast (e.g., Fig. 14) there are limited depth soundings with often no more than one sounding per kilometre. This produced a series of bull's-eyes like rings when interpolated with coastal points in an inlet, because the more numerous high water line points skew the interpolation by contributing a larger proportion to the area weighted calculation of the interpolated points. This creates depth values shallower than the actual depths. The "pits" in the center of the inlet thus represent the actual depth observations and more closely reflect the correct depth throughout the center of the inlet.

A similar effect occurs at some deeper locations where the soundings are more dispersed and follow a distinct pattern corresponding to the track lines on which data were collected. Often, the distances between neighbouring track lines are greater than 20 m, generating two issues for the natural neighbour interpolation. First, the natural neighbour method preserves all input points in the resulting surface grid, producing distinct points in areas with limited depth soundings in the DEM. Secondly, when grid cells between the ship track lines are interpolated the neighbourhood of points may include points some distance away, incorporating a large area with a larger range of depth values for the area weighted calculation. This large neighbourhood may skew the interpolation and produce shallower depth values for the interpolated cells. The result will be the appearance of erroneous deeper tracks or pits in a line surrounded by a larger area of shallower depth values, when in fact, like in the inlets, these deeper tracks represent the actual observations, and it is the surrounding area that are likely deeper than they appear in the 20 m DEM. This effect is best observed when slope is calculated from the 20 m DEM as it highlights the dramatic rate of change (Fig. 15). The exact distance from the shoreline where deeper waters begin to be misrepresented due to field sheets data density is variable from location to location throughout the study area.

MODEL DOMAIN

A model domain is defined here as the region of greatest utility. Areas outside the model domain will have a higher incidence of spatial anomalies and inaccurate depths and should be used with caution. The domain of the series of 20 m DEMs is constrained by data density, as discussed above. An extensive visual assessment of all the 20 m models indicates this domain should be limited to areas of 50 m depth or shallower, based on the greater density of soundings in shallower waters (Fig. 4 and 5). Although there are many locations deeper than 50 m where there is dense coverage of input data points the authors feel that restricting the domain to this depth range for spatial analysis over large areas of the coast will avoid potential inaccuracies in deeper areas resulting from interpolations with low data densities (Fig. 15). Each model was extended 5 km inland and 5 km deeper than the 50 m depth contour to allow for the creation of bathymetric derivatives for the entire model domain of 0 – 50 m (Appendix B).

RASTER VERSUS VECTOR

Bathymetric features can be displayed within a GIS in either raster or vector format. Each format has its intended purpose, and its limitations. Vector data are often used to represent bathymetric classes, either as contours (polylines) or as zones (polygons). Manual editing of line work can be used to smooth features. This element of cartographic artistry is often used to more accurately represent areas of limited data or high topographic change. Vector data are not restricted to a fixed resolution and therefore any elevation values of interest (i.e. 50 m contours) can be visualised in a spatial layer by drawing contour lines. In steep locations, the distance between the contour lines will be dramatically reduced to symbolize this abrupt change. Interpolated raster layers can struggle with areas of limited depth soundings or steep geographical features creating anomalies, especially when the rate of topographic change exceeds the raster resolution, creating a blocky output (Fig. 13). However, the fixed resolution of raster layers allows bathymetric derivatives such as slope, aspect, and rugosity to be calculated. These describe the rates of change of the bathymetric layer and define localized geographical variation. Raster data can thus support a wider range of spatial analyses and modelling exercises, while vector data are likely better suited to supporting map making and communicating the results of any analyses, particularly in complex coastal regions like Pacific Canada.

BENEFITS AND POTENTIAL APPLICATIONS

The series of 20 m DEMs presented here are the first, comprehensive bathymetric grids to resolve important nearshore features unrepresented on any previous bathymetry in Pacific Canada. This increased resolution will contribute to improved research and decision making in coastal waters and at the land-sea interface, playing a significant role in planning, risk assessment, and resource management decisions (Li and Heap 2008). Marine-use planning initiatives, emergency spill response plans, and studies of species and habitat distributions will all benefit from the improved precision of this product. Such applications increasingly require a more detailed understanding of the topographic features in the nearshore region than previously available.

Additionally, by extending the 20 m DEMs across the nearshore and intertidal region into the terrestrial region, estimates of the impacts of natural and anthropogenic terrestrial processes on the coastal zone will be more accurate and precise. This increased accuracy will improve future spatial analyses. For example, including land elevations for 5 km in the neighbourhood of cells used to calculate bathymetric derivatives such as broad BPI yields more accurate values in the nearshore because adjacent land is not assumed to be flat (a typically implicit assumption when calculating bathymetric derivatives) (Haggarty and Yamanaka 2018).

The 20 m DEMs are a precursor to several other spatial layers and tools being developed for spatial analysis and modelling. The 20 m DEMs have been used to create a model of rocky substrate for inshore Rockfish (Haggarty and Yamanaka 2018), as well as the development of a bottom patch polygon layer that delineates locations by depth and substrate type (Gregr et al. 2013). Bathymetric derivatives, specifically rugosity, curvature, and broad BPI, as well as depth were incorporated into the health assessment of glass sponge reefs within the Strait of Georgia (Dunham et al. 2018) and to assess habitat in Rockfish Conservation Areas (DFO 2019). In addition to serving as a framework for future spatial analyses, the 20 m DEMs provide sufficient resolution to support stratification in survey design, or identify target depth ranges or specific bathymetric features.

CONCLUSIONS

Creating this series of 20 m DEMs involved validating and interpolating data along a complex coastline over 25,000 km long comprised of geographical features including long shallow bays, deep fiords, and thousands of islets. The final 20 m DEMs represent an amalgamation of the most appropriate, available data and provides a higher resolution for the nearshore region than any previously available. Due to the loss of input data density with depth, the recommended domain of these DEMs is 50 m and shallower. Deeper areas may also be accurately represented depending on localized point density.

The development of models is always an iterative process and an update of this bathymetry is thus recommended as more precise data become available. Improvements to the 20 m DEMs could include incorporating waters deeper than 50 m, utilizing crowd-sourced depth soundings (Novaczek et al. 2019), refinements to the calculation of the high water line elevation, and through more complete and regular integration of available MBES data. Addressing the potential discontinuity at the high water line would also improve accuracy in some local areas.

This first high resolution bathymetric coverage of Pacific Canadian waters provides unparalleled detail of the coastal zone, including the adjacent terrestrial area. It is hoped this increased detail will contribute to ongoing and future research projects and decision making needs in this dynamic, productive region of Canada's oceans.

ACKNOWLEDGMENTS

The authors thank the staff of the Canadian Hydrographic Service and Natural Resources Canada for the data incorporated into this model. We thank Mesha Sagram for her GIS support, and Cole Fields for the valuable comments he provided to this manuscript. We also thank Dana Haggarty for her thorough quality control efforts throughout the development of this model and for reviewing this manuscript.

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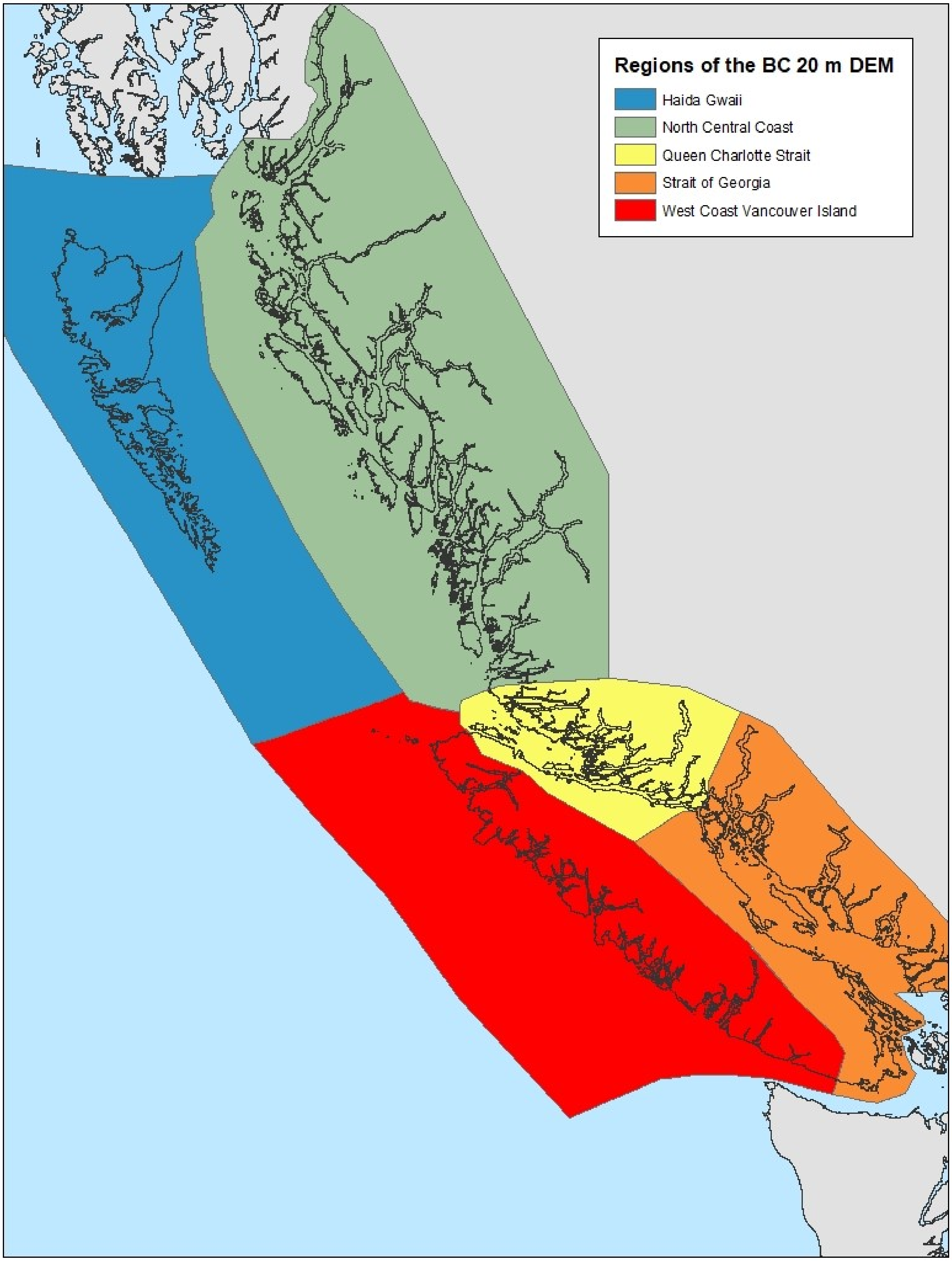

Figure 1: Regions of the coast of British Columbia used for the development of the 20 m bathymetric DEMs.

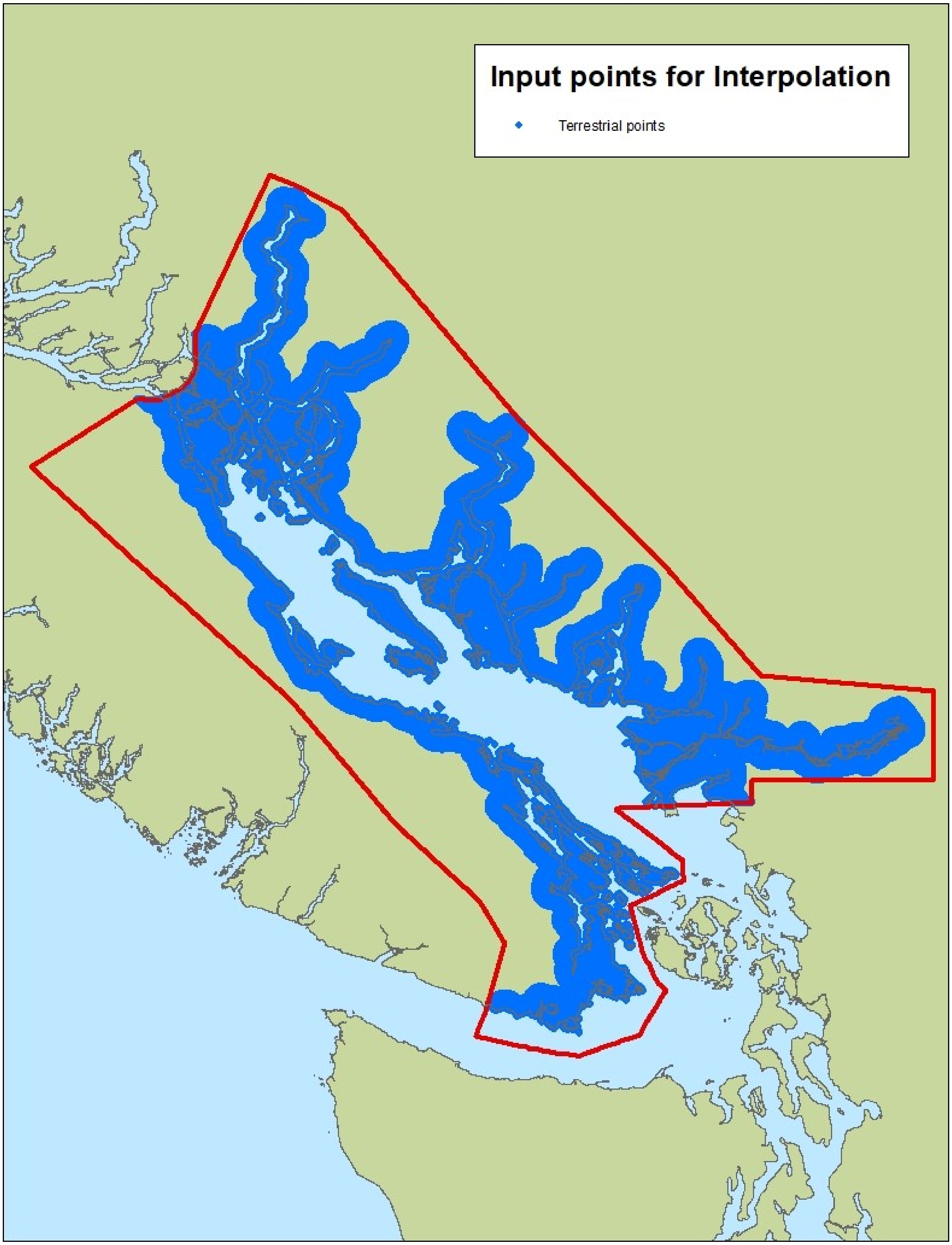

Figure 2: Extent of terrestrial input points used in the natural neighbour interpolation for the Strait of Georgia.

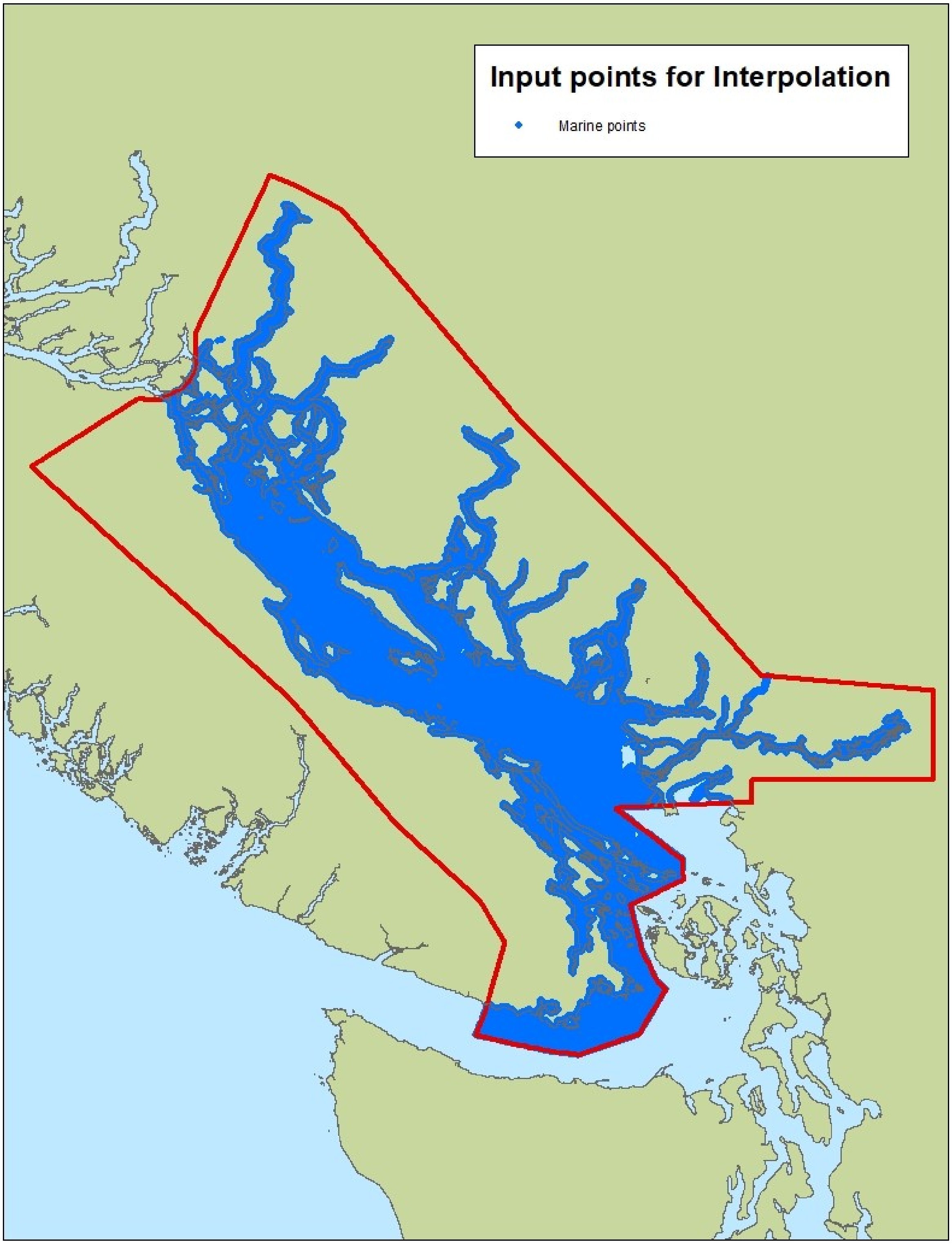

Figure 3: Extent of marine input points used in the natural neighbour interpolation for the Strait of Georgia.

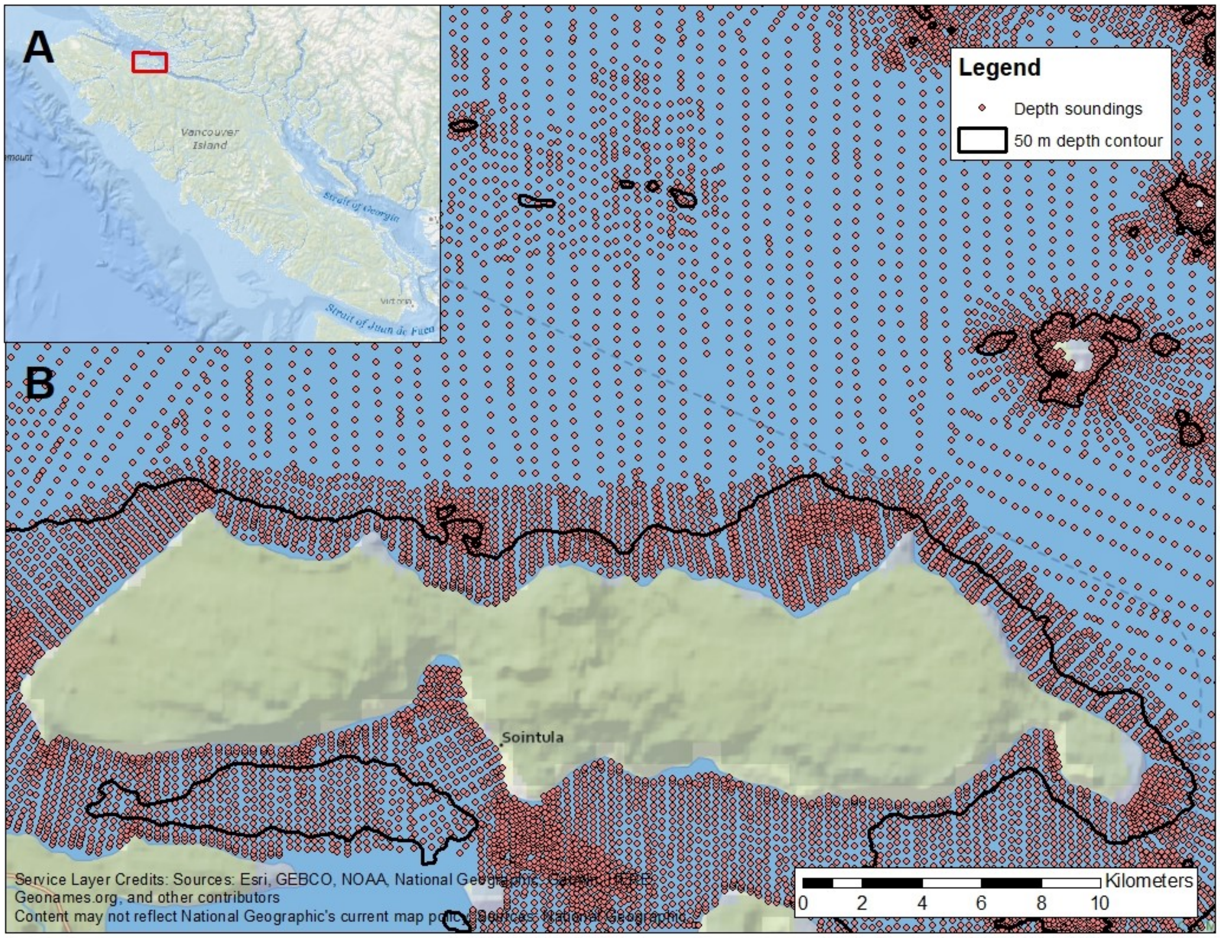

Figure 4: Variation in density of Canadian Hydrographic Service depth soundings near Malcolm Island, Queen Charlotte Strait (A). A higher density of depth soundings are found closer to the shorelines and depth soundings are more sparsely distributed through the middle of the strait (B).

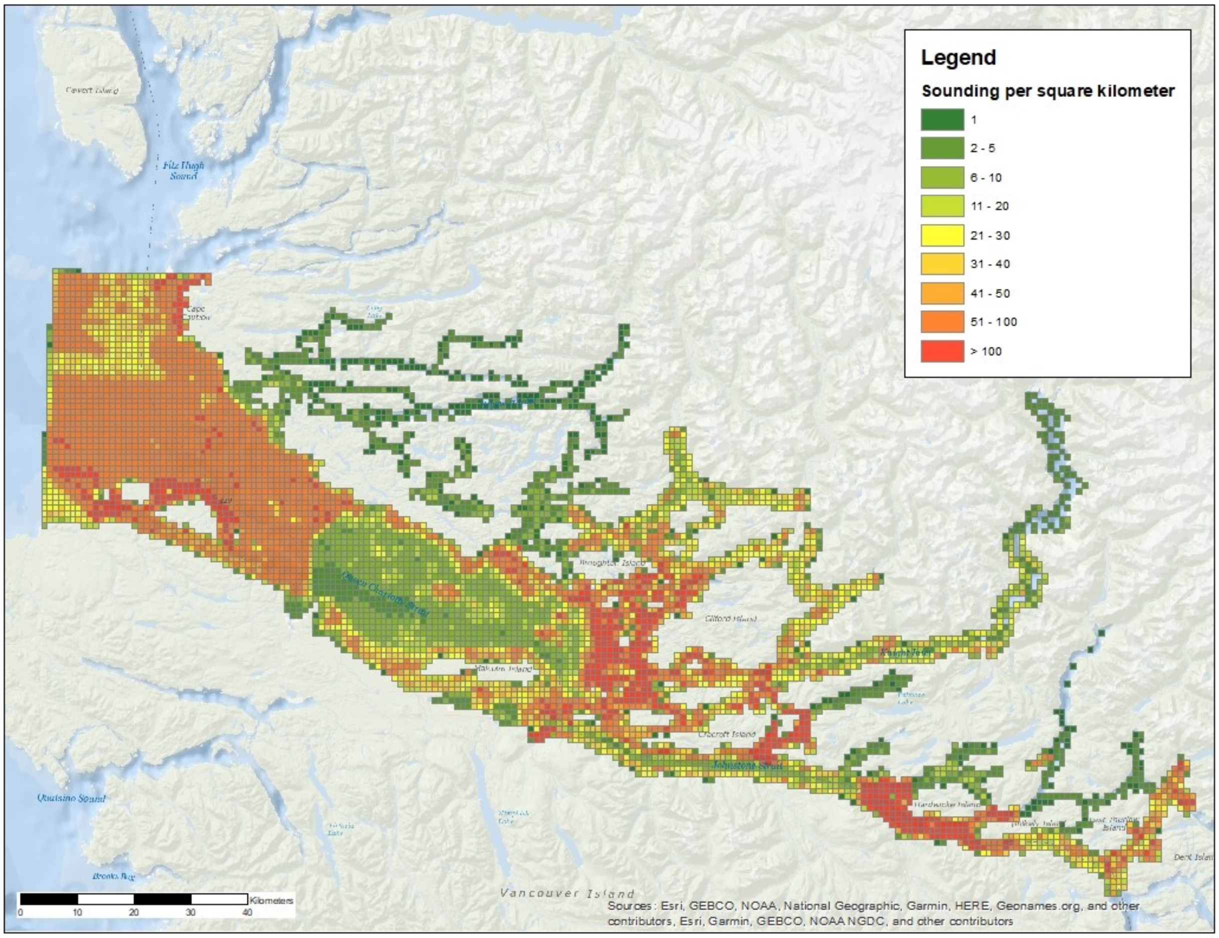

Figure 5: Variation in density of depth soundings per square kilometer for the Queen Charlotte Strait region.

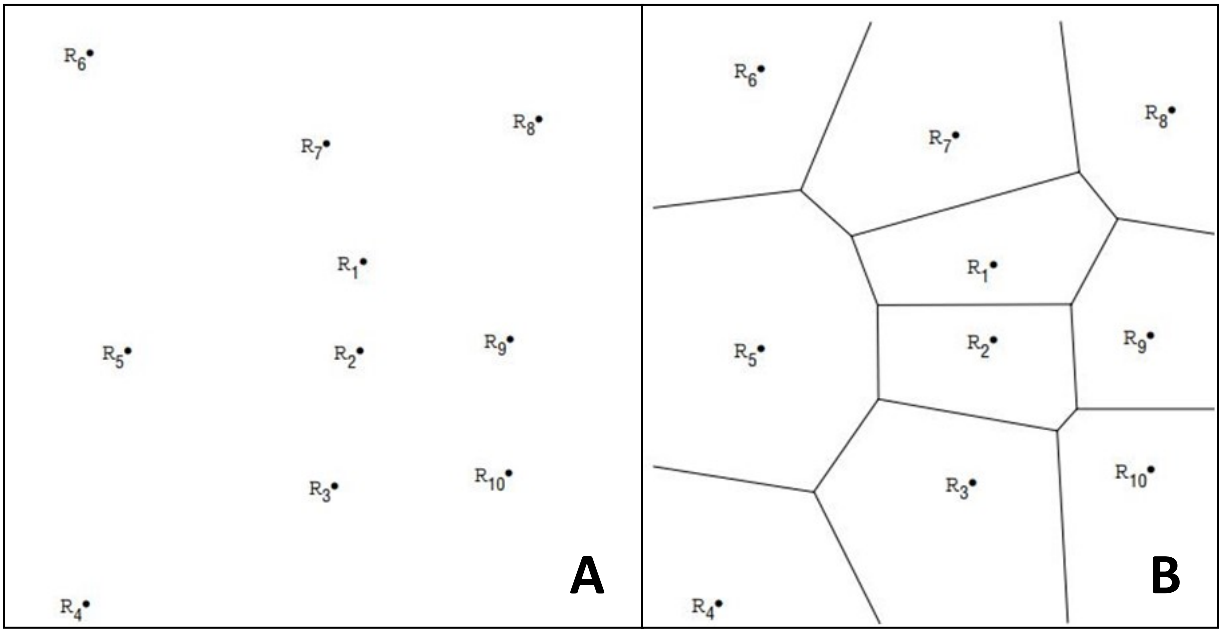

Figure 6: (A) A set of reference points, R; (B) Thiessen polygons (Voronoi polygons) built from the original set of reference points (Boots 2005).

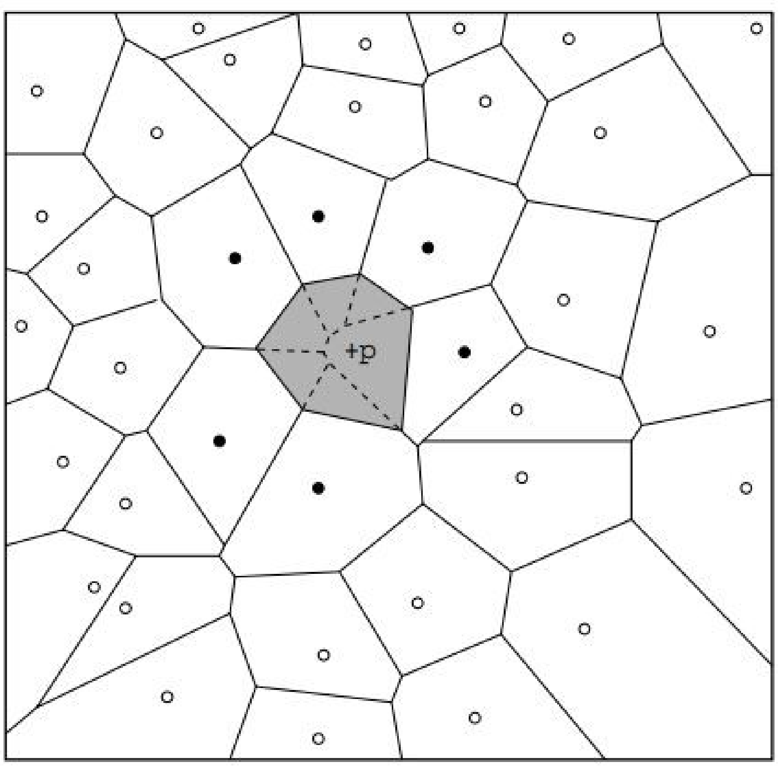

Figure 7: Within a set of Thiessen polygons, the natural neighbour of any new point (+p) is determined by the number of neighbouring polygons (•) and the area of overlap for each neighbouring polygon, shaded grey (Boots 2005).

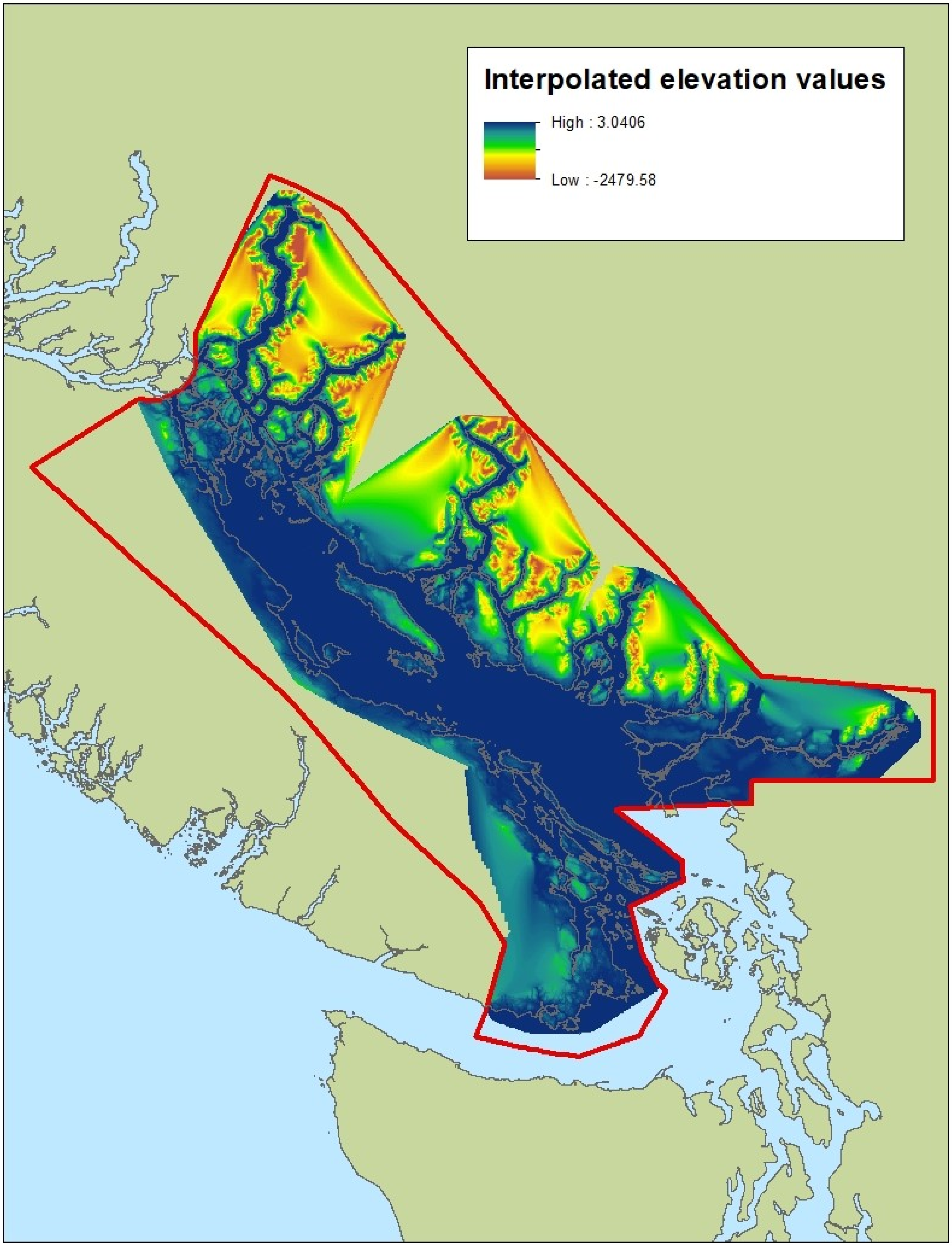

Figure 8: Results from the natural neighbour interpolation of the terrestrial dataset in the Strait of Georgia. Interpolation extends to the bounding box of input data points. Note that all positive values are marine depths and negative values are terrestrial elevations.

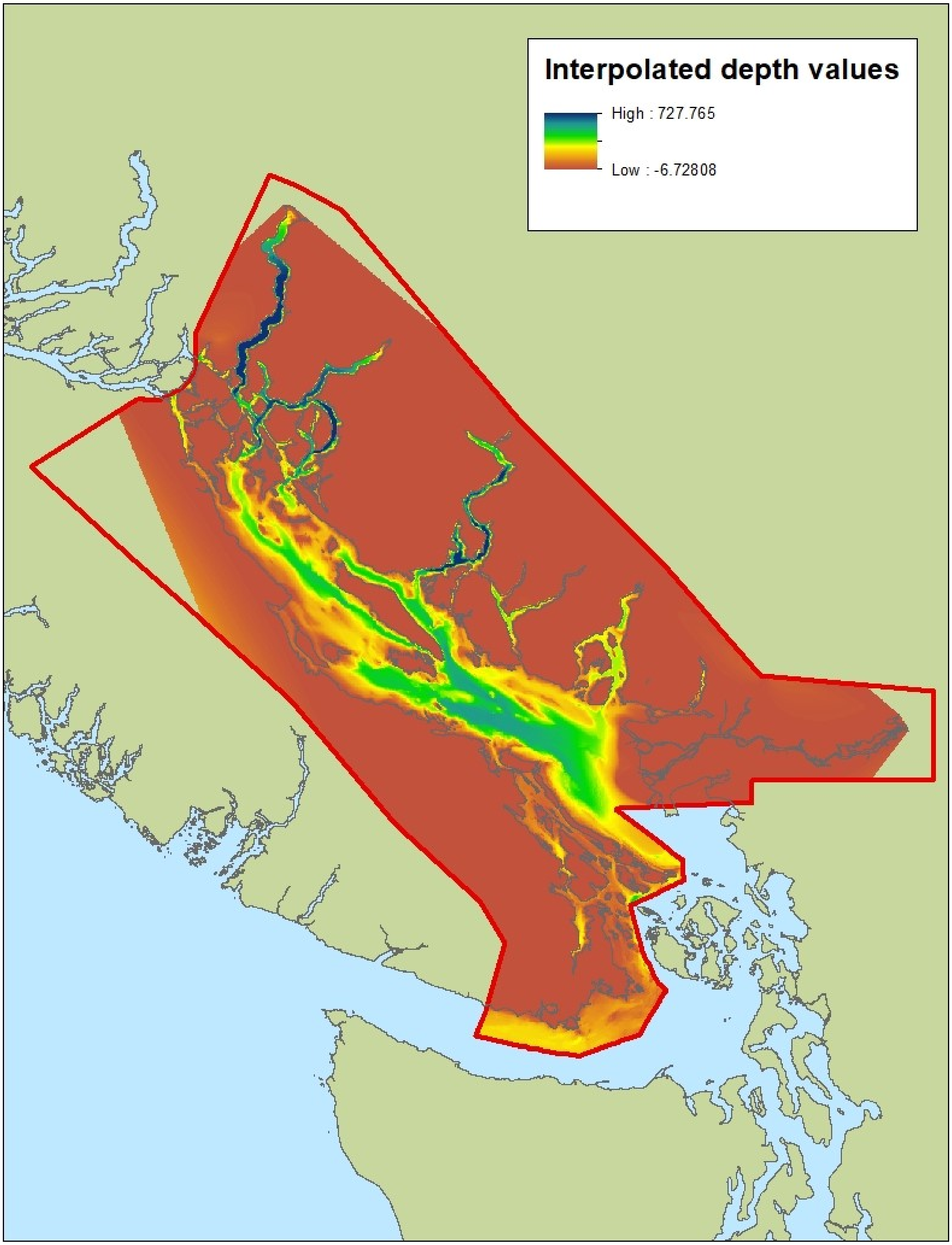

Figure 9: Results from the natural neighbour interpolation of the marine dataset in the Strait of Georgia. Interpolation extends to the bounding box of input data points. Note that all positive values are marine depths and negative values are terrestrial elevations.

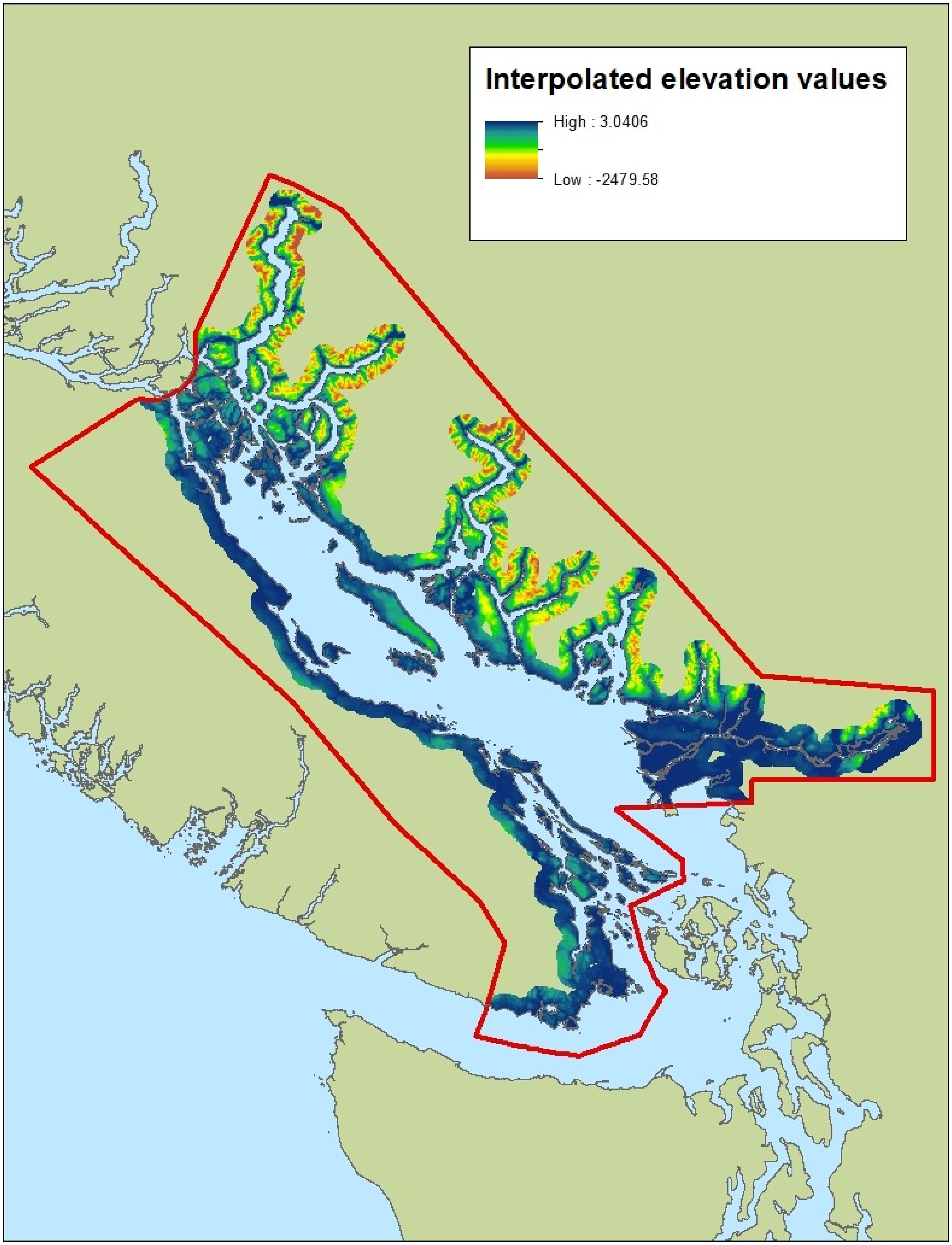

Figure 10: Natural neighbour interpolation of the terrestrial dataset in the Strait of Georgia after marine areas have been masked out. Note that all positive values are marine depths and negative values are terrestrial elevations.

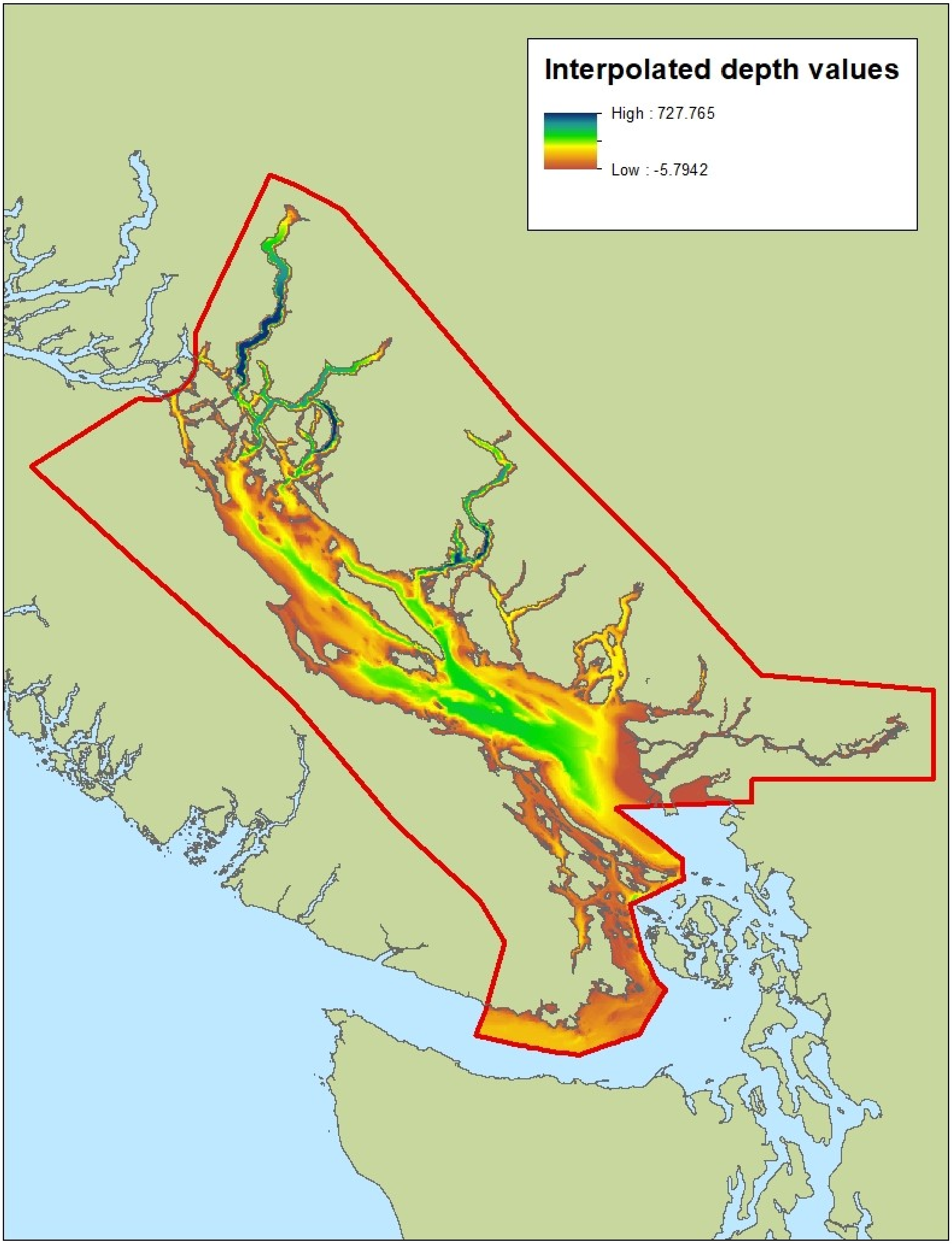

Figure 11: Natural neighbour interpolation of the marine dataset in the Strait of Georgia after terrestrial areas have been masked out. Note that all positive values are marine depths and negative values are terrestrial elevations.

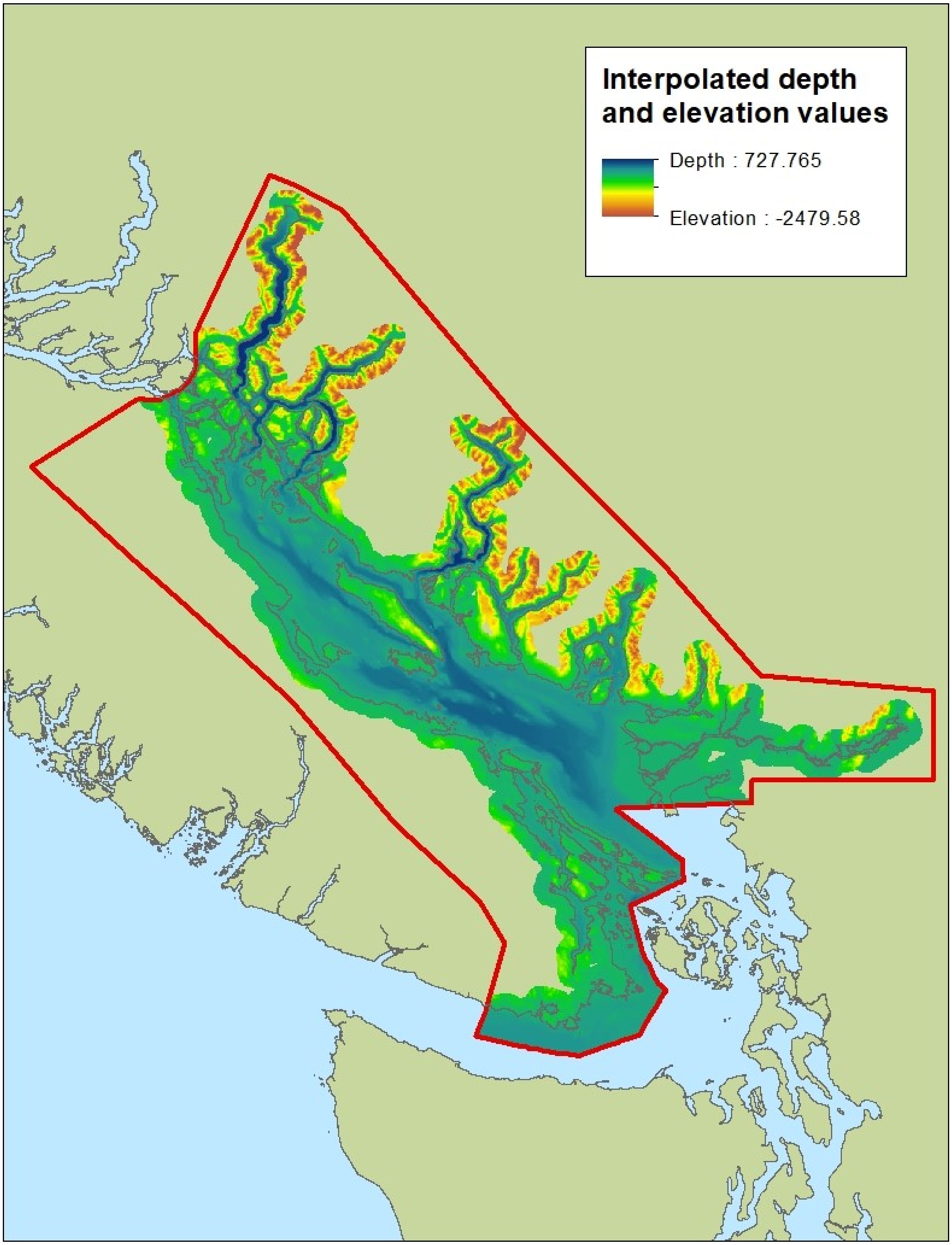

Figure 12: Strait of Georgia 20 m DEM created by combining the marine and terrestrial natural neighbour interpolation rasters using ArcGIS Raster Calculator. Note that all depth values are positive and negative values are terrestrial elevations.

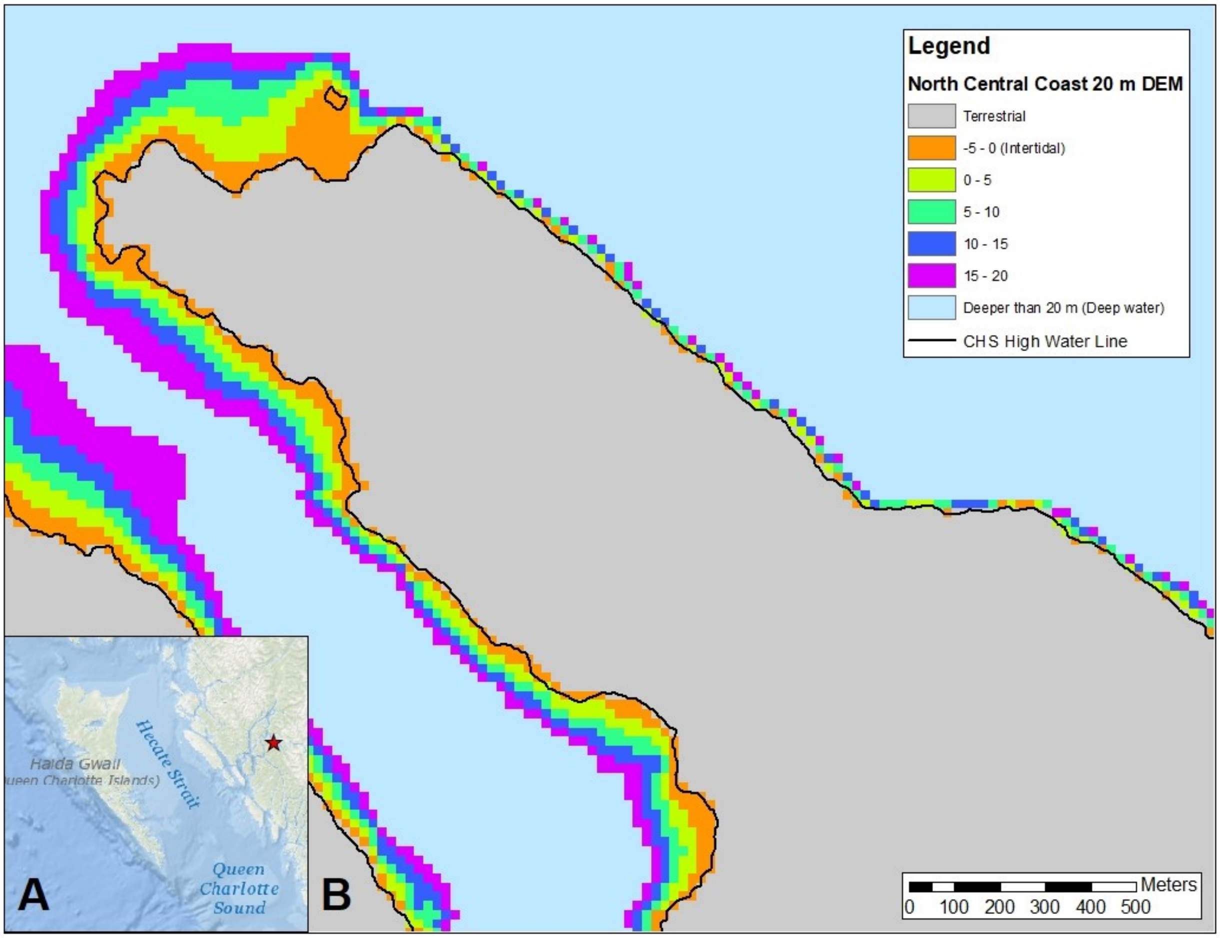

Figure 13: Cliff features along a peninsula in Gardner Canal (A) where large changes in depth along the northeast side of the shoreline create a disjointed appearance when compared with gently sloping beach features along southwest side in the 20 m DEM (B). All marine depths are positive and terrestrial elevations are negative.

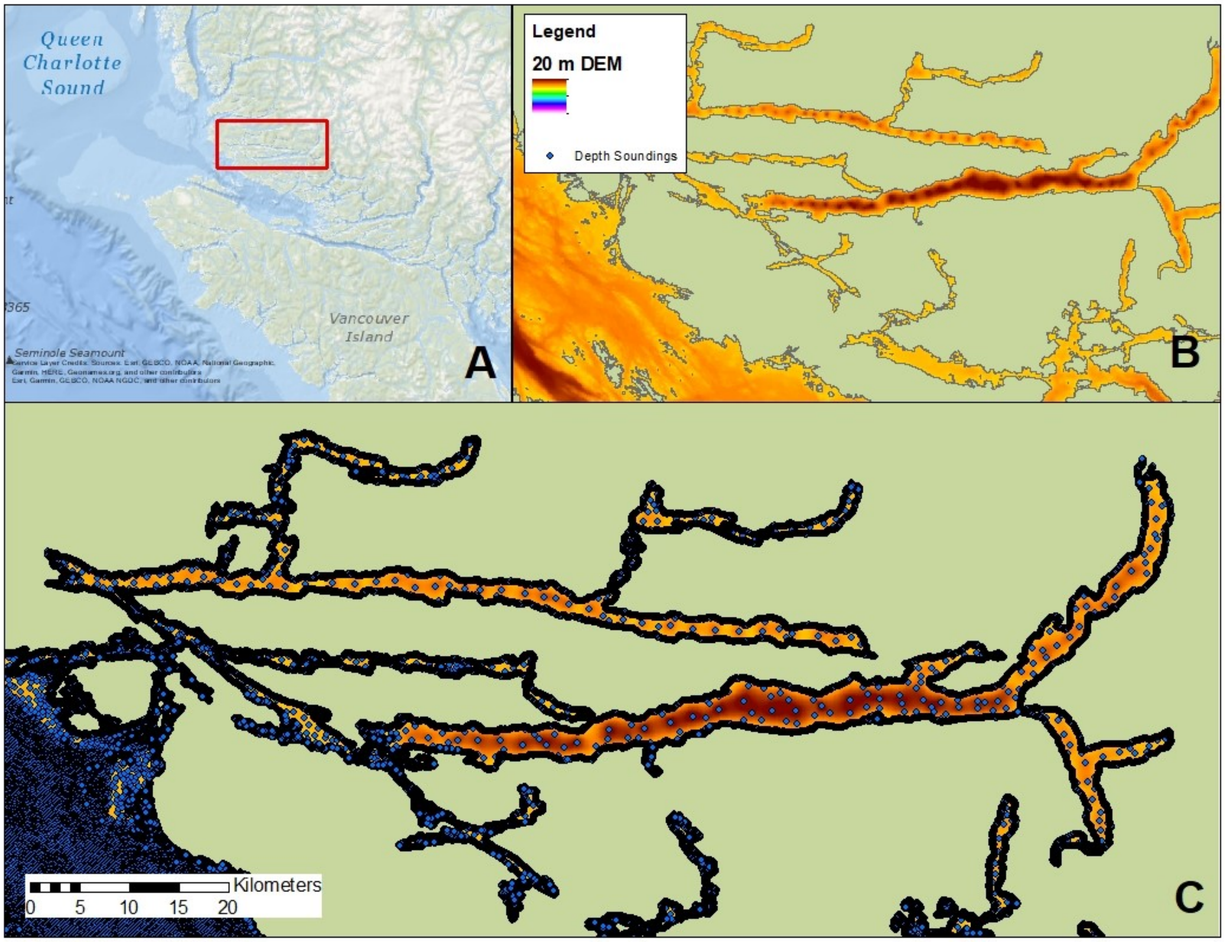

Figure 14: Bull's-eye like rings in Belize Inlet (A) due to limited depth soundings throughout the middle of the inlet (C). The pits in the center of the inlet more closely reflect the depth throughout the center of the inlet than the interpolated values (B).

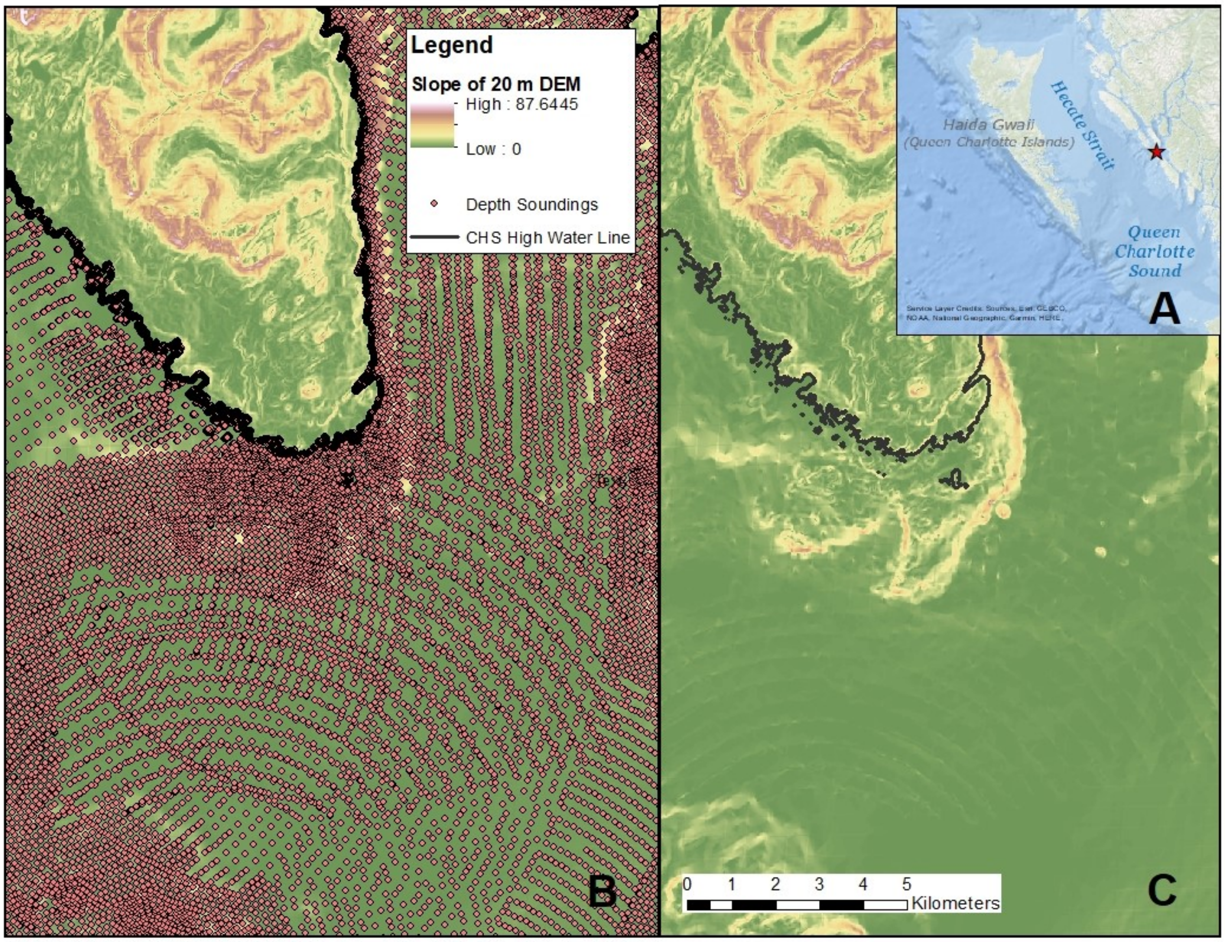

Figure 15: Limited depth soundings along linear track lines in deeper waters south of Campania Island (A & B) creating the misleading appearance of pits in a line (C). The derived slope of the 20 m DEM highlights the rapid change in depth in areas where a large neighborhood size was used for the natural neighbour interpolation.

APPENDICES

Appendix A: Summary of point data from field sheets and additional sources

20 m DEM Region	Dataset	Data Source	Number of Points
Strait of Georgia	Terrestrial (29,940,185 points)	Canadian Digital Elevation Data	29,261,905
		High Water Line	678,183
		B.C. Rocks	97
	Marine (12,598,020 points)	Field sheets	6,738,477
		High Water Line	678,183
		B.C. Rocks	3,879
		B.C. Soundings	544,974
		Digitized points	983
		Multibeam resampled to 40 m	4,581,954
		Multibeam resampled to 100 m	49,570
Queen Charlotte Strait	Terrestrial (19,899,552 points)	Canadian Digital Elevation Data	19,376,613
		High Water Line	522,836
		B.C. Rocks	103
	Marine (817,087 points)	Field sheets	287,718
		High Water Line	522,836
		B.C. Rocks	2,309
		S57 Soundings	3,575
		Digitized chart points	649
North Central Coast	Terrestrial (68,066,538 points)	Canadian Digital Elevation Data	66,764,352
		High Water Line	1,287,230
		B.C. Rocks	189
	Marine (13,040,097 points)	Field sheets	11,641,829
		High Water Line	1,287,230
		B.C. Rocks	11,859
		B.C. Coast Soundings	260,379
		S57 Soundings	12,702
		Multibeam resampled to 40 m	45,382
		Digitized chart points	44
Haida Gwaii	Terrestrial		Not available
	Marine (1,906,355 points)	Field sheets	601,162
		B.C. Soundings	110,868
		S57 Soundings	182
		NOAA depth soundings	500
		Multibeam points	Not available
		Digitized chart points	46
		Points derived from CHS intertidal polygon	1,304,465
West Coast Vancouver Island	Terrestrial		Not available
	Marine (3,063,466 points)	Field sheets	1,391,495
		B.C. Soundings	24,409
		Points derived from CHS intertidal polygon	1,647,562

Appendix B: 20 m DEM models

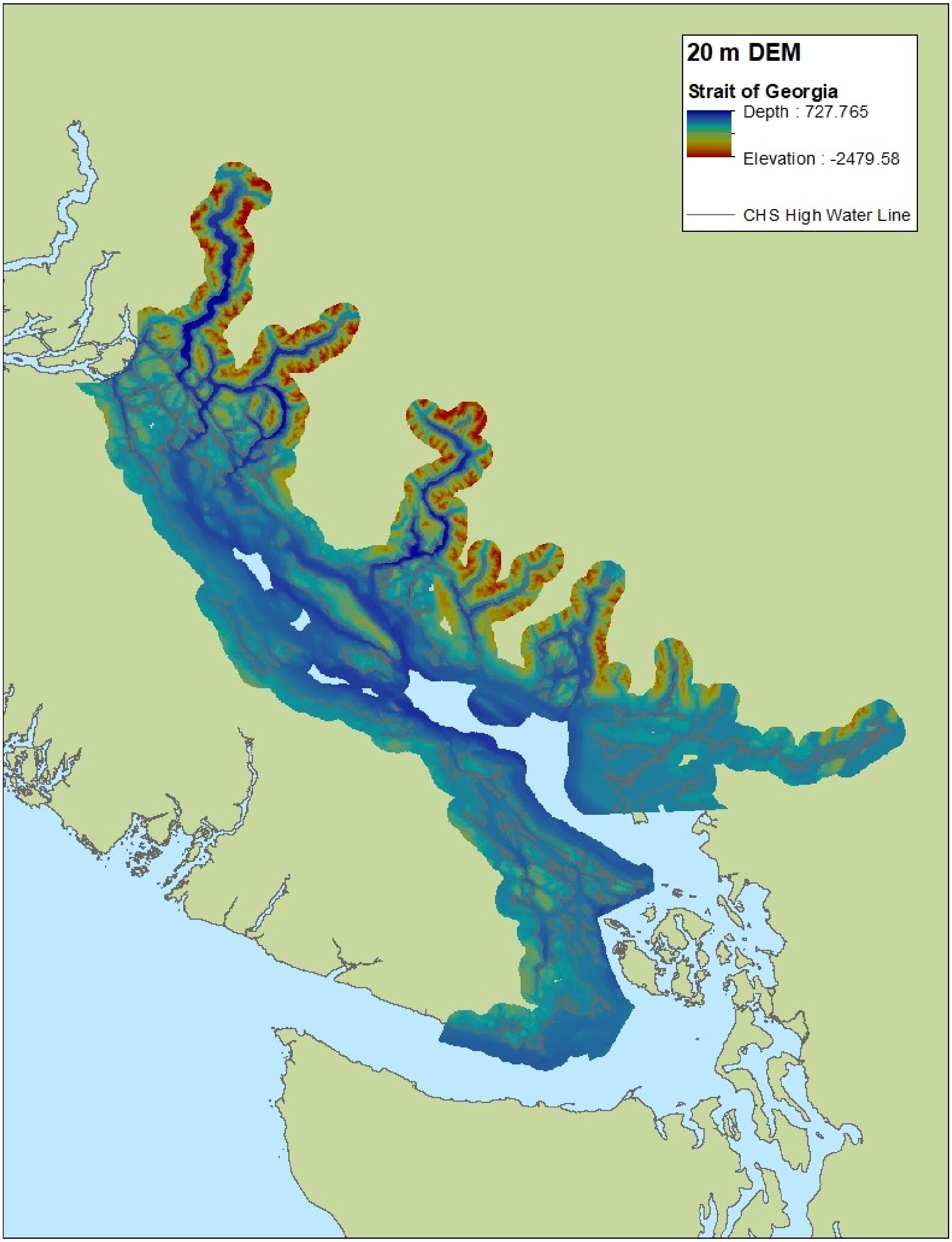

Figure B1: Strait of Georgia 20 m DEM with the inclusion of areas extending from 5 km inland of the high water line to 5 km beyond a depth of 50 m, to allow for the calculation of bathymetric derivatives.

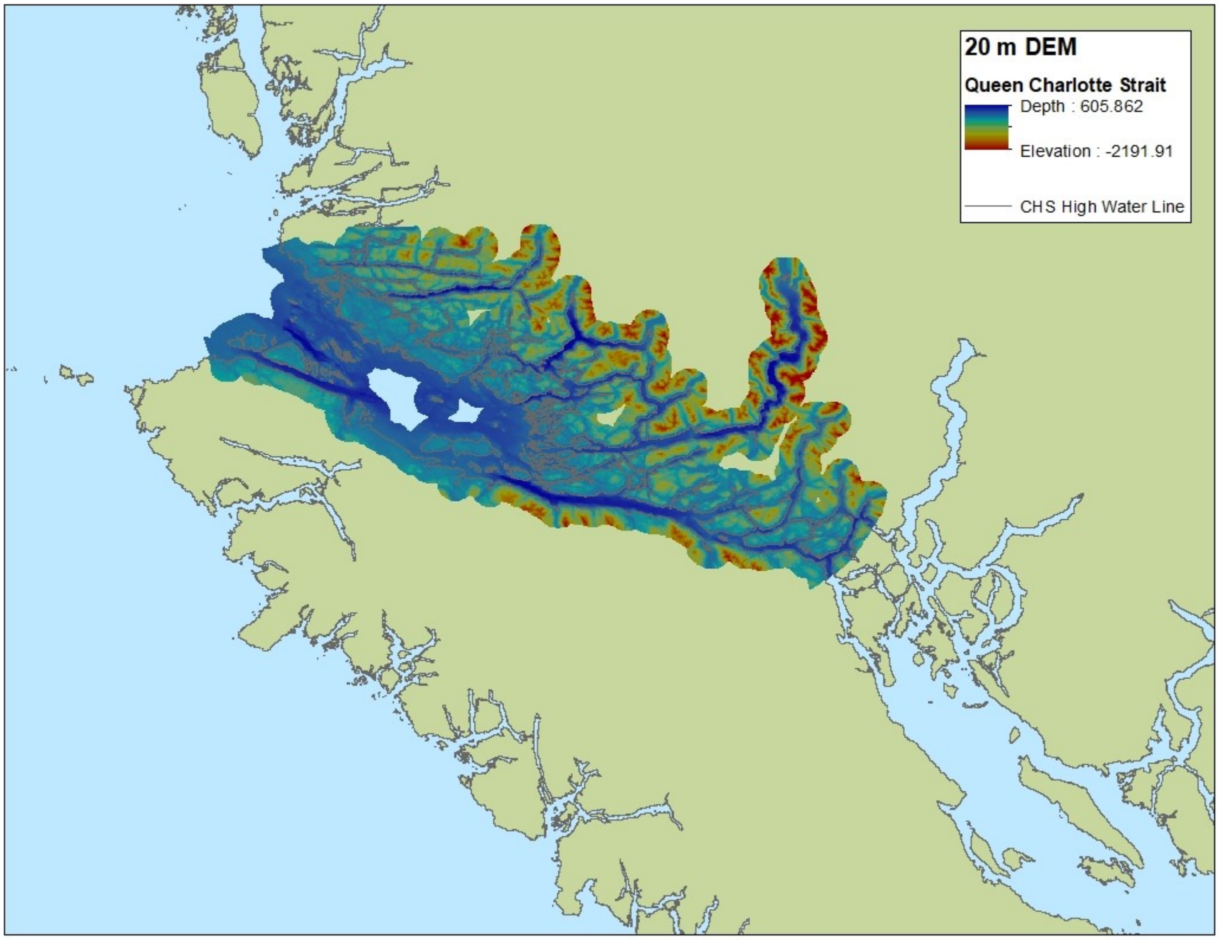

Figure B2: Queen Charlotte Strait 20 m DEM with the inclusion of areas extending from 5 km inland of the high water line to 5 km beyond a depth of 50 m, to allow for the calculation of bathymetric derivatives.

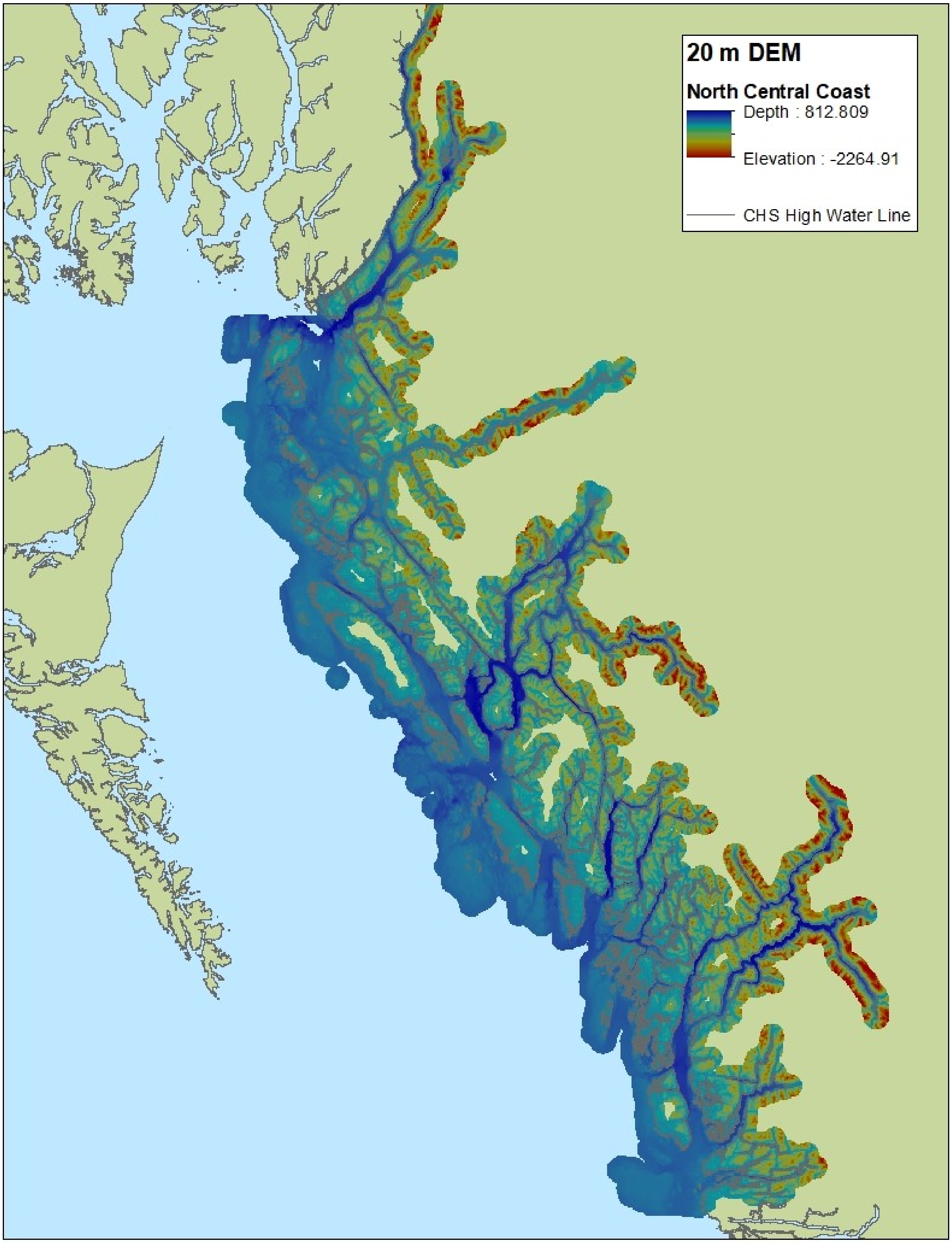

Figure B3: North Central Coast 20 m DEM with the inclusion of areas extending from 5 km inland of the high water line to 5 km beyond a depth of 50 m, to allow for the calculation of bathymetric derivatives.

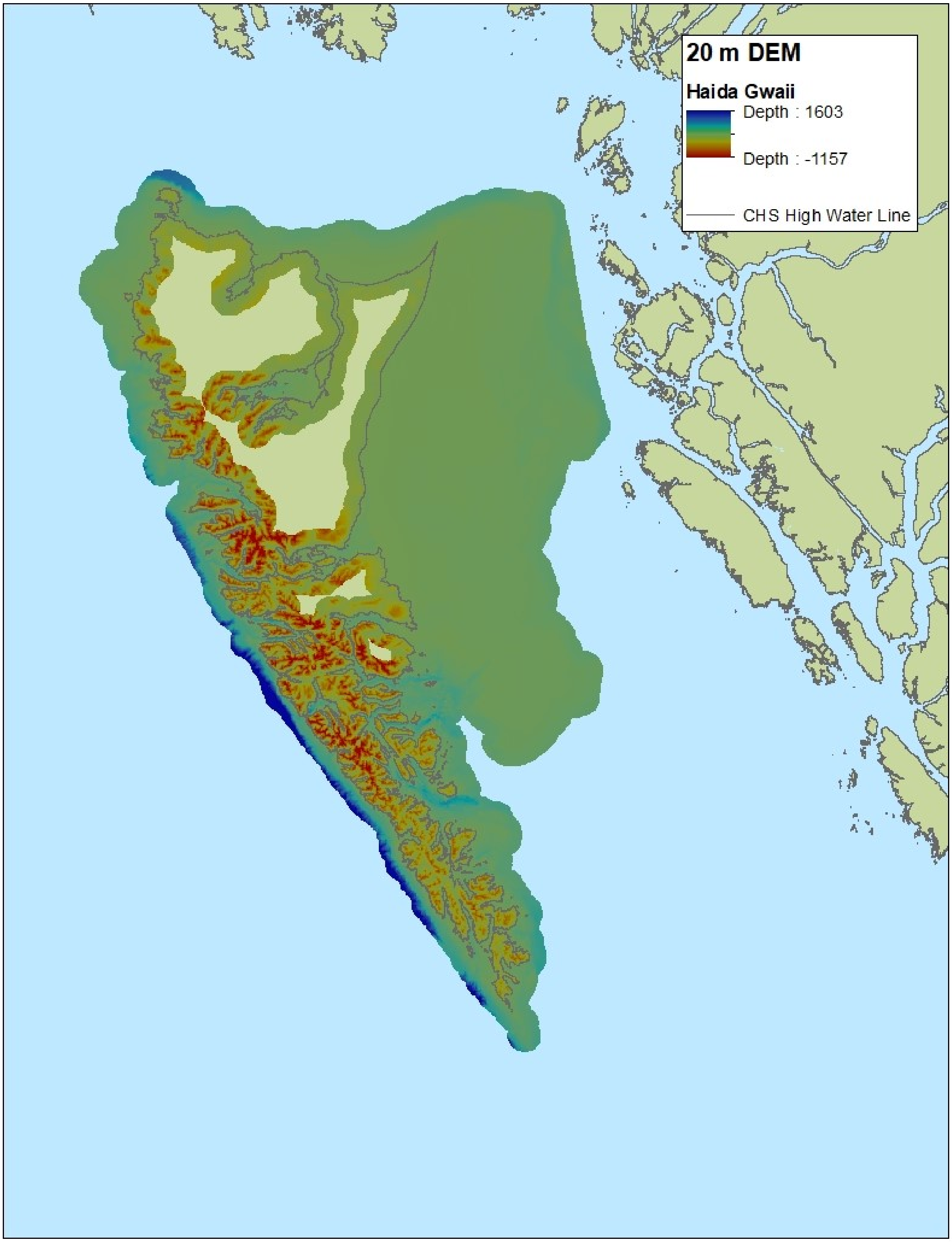

Figure B4: Haida Gwaii 20 m DEM with the inclusion of areas extending from 5 km inland of the high water line to 5 km beyond a depth of 50 m, to allow for the calculation of bathymetric derivatives.

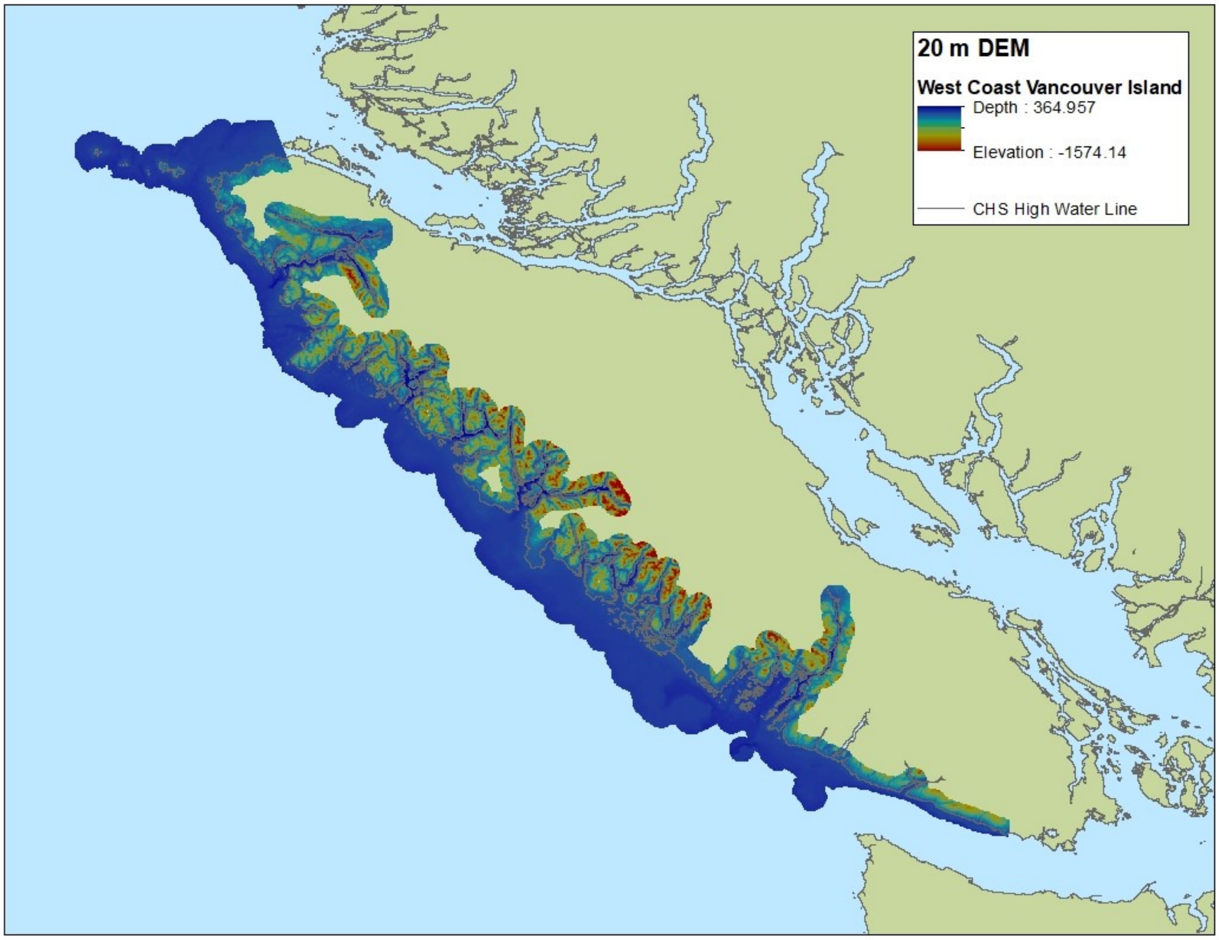

Figure B5: West Coast Vancouver Island 20 m DEM with the inclusion of areas extending from 5 km inland of the high water line to 5 km beyond a depth of 50 m, to allow for the calculation of bathymetric derivatives.