Inventory and assessment of tidal energy resources near northern communities part 2: numerical tide modelling

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Inventory and Assessment of Tidal Energy Resources Near Northern Communities Part 2: Numerical Tide Modelling

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Executive Summary

Polar Knowledge Canada (POLAR) desired to investigate and assess the potentially exploitable tidal energy resources located near communities in northern Canada and make this information available to stakeholders through a software application/tool with functionality for geospatial analysis and interactive mapping. This second work package constituted the development of a numerical model to simulate spatial and temporal variation of tidal flows and hydrokinetic energy near the four northern communities selected in the first work package; Cape Dorset, Igloolik, Iqaluit and Kuujjuaq. The numerical model was developed using the methodology proposed in the International Electro Commission standard: Tidal Energy Resource Assessment and Characterization (62600-201:2015). This provides a standardized methodology that ensures consistency and accuracy in the estimation, measurement, characterization and analysis of the theoretical tidal currents. From the standard, the methodology from Stage 1 was used to develop and validate the model, and to calculate the annual energy density, velocity probability distribution and annual energy production. Other characteristics that impacts the tidal resource assessment, such as ice cover, ice debris, vertical velocity variation, sediments and mounting arrangement are also discussed in this report.

Hotspots were identified near all four northern communities. Cape Dorset has a few hotspots with average speeds of 0.75 to 1.5 m/s, which tends to be on the low end for potential hydrokinetic energy sites. Most tidal energy turbines have a cut-in speed of 1.0 to 1.5 m/s, and thus would not generate energy for significant periods of time at Cape Dorset. The Labrador Narrows, 50 km from the Igloolik community, has average speed of 2.0 m/s and can attain maximum speed of 5 m/s (50 MWh/m^2). Depth varies from 50 to 100 m with limited shallow spots, which can be quite challenging for turbine deployment, operation and maintenance. As for Iqaluit, there is limited amount of hydrokinetic energy near the community. However, there is a lot of hydrokinetic energy between the Frobisher Bay Islands, 50 to 100 km away from the community. The average speed is around 1.5 m/s and the maximum speed is around 3.5 m/s (20 MWh/m^2) per year. Kuujjuaq is the most promising site with significant hydrokinetic energy (10-60 MWh/m^2 per year) along the Koksoak River: from the Kuujjuaq community to the mouth of the river (50 km away from the community). The average speed is around 1.75 m/s with maximum speed of 6.0 m/s. With depths varying from 5 to 30 m and ice covered 8 months of the year from mid-November to mid-July, a bottom mounted turbine would be feasible in terms of deployment, operation and maintenance.

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1. Introduction

The National Research Council (NRC) is the Government of Canada's premier research organization supporting industrial innovation, the advancement of knowledge and technology development, and fulfilling government mandates. The NRC's Ocean, Coastal and River Engineering (NRC-OCRE) Research Centre supports a broad cross-section of industry sectors by developing creative and practical solutions to engineering challenges in rivers, lakes and marine environments, with a particular focus on harsh and extreme conditions. The NRC-OCRE provides expertise and tools to identify, adapt, and integrate advanced solutions into systems that improve the performance and safety of ocean, coastal, and marine operations, meet the challenges of climate change, and protect infrastructure, property and people from severe weather events and other environmental risks. The NRC-OCRE owns and operates comprehensive test facilities, including ice tanks, wave basins, wave flumes, and state-of-the-art numerical hardware and tools, located both in St. John’s and Ottawa.

The NRC-OCRE has prepared this report as part of Work Package 2 as documented in the NRC-OCRE Proposal PL200067, “Inventory and Assessment of Tidal Energy Resources Near Northern Communities.” The three work packages described in the proposal were developed in response to needs identified by Polar Knowledge Canada (POLAR). POLAR desired to investigate and assess the potentially exploitable tidal energy resources located near communities in northern Canada and make this information available to stakeholders through a software application/tool with functionality for geospatial analysis and interactive mapping. The first Work Package constituted a preliminary assessment of prior tidal energy resource assessments, energy needs in northern communities, and available oceanographic and energy use data to support future tidal energy modelling efforts. The second Work Package focused on developing a numerical model to predict the spatial and temporal variation of tidal flows and hydrokinetic energy near several northern communities identified in Work Package 1. In the third and final Work Package, the NRC-OCRE will develop a digital web or desktop atlas with best available information on tidal energy resources for regions where focused modelling was completed in Work Package 2.

1.1. Background

Canadian marine renewable energy, including wave, tidal and river energy, has gained interest from developers as a source of clean energy, particularly as an energy solution for remote communities in Canada. Of the three popular marine renewable energy sources, tidal energy has gained some momentum within Canada primarily due to the Bay of Fundy and its world-renowned tidal range. However, an initial study of Canada’s tidal energy potential has shown that Canada has 190 individual tidal power sites where the potential mean power is estimated to be greater than 1 MW [1], illustrating the potentially vast tidal energy resource that lies within Canadian waters. Due to limited available data on the tidal flows in many of the potential tidal energy sites within Canada, the estimated mean potential power remains highly uncertain.

There has been an effort in developing a more thorough understanding of the tidal energy resources within Canada, with a number of studies assessing the tidal energy potential along the Pacific and Atlantic coasts. Sutherland *et al.* [2] assessed the tidal energy potential within the Johnstone Strait at Vancouver Island and found that the estimated total tidal power potential from 12 sites within the Strait is 767 MW. Blanchfield *et al.* [3] conducted a study of only the M2 tidal constituent around Masset Sound, Haida Gwaii (northern British Columbia) and found an estimated 79 MW of extractable power averaged over a tidal cycle.

More effort has been put into characterizing the tidal energy potential on the Atlantic coast; primarily around the Bay of Fundy and the Minas Passage region (Yang *et al.* [4]; Karsten [5]; and Karsten *et al.*, [6]; among others). Hagerman *et al.* [7] identified eight potential tidal energy sites around Nova Scotia with mean extractable power (defined at 15% of the mean total depth-averaged power) ranging from 6.5 MW to 166 MW.

There has been very limited work in the assessment of Arctic coast tidal energy potential. The majority of the studies in Canada's Arctic waters focus on the modelling of tidal water elevations (Kleptsova & Pietrzak, 2018 [8]; Chen *et al.* [9]; Hannah *et al.* [10]; and Kagan & Sofina [11]). Guo *et al.* [12] modelled the tidal hydrodynamics within the Canadian Arctic Archipelago, however the study did not focus on assessing potential tidal energy. The goal of the present study is to further develop the accuracy of the tidal energy potential of the Arctic coasts, building on the work of Cornett [1].

1.2. Methodology

A number of methods have been employed to conduct tidal resource assessments with varying degrees of complexity. The simplest method is to use analytical models, which have been used in the past by Bryden *et al.* [13] and Garret & Cummins [14] to produce reasonable results for specific, simplified scenarios, i.e. a straight tidal channel with constant bathymetry. These methods have been shown to be able to predict the tidal energy with some degree of accuracy. For instance, Sutherland *et al.* [2] showed the analytical model by Garret & Cummins [14] was able to predict available tidal energy to within 10% of their calibrated numerical model. However, these analytical models are impractical to apply to large, complex domains.

A number of numerical modelling studies have successfully assessed the tidal potential of different sites around the world utilizing either two-dimensional or three-dimensional hydrodynamic models with varying model domain sizes, computational grid resolutions, simulation lengths and driving boundary conditions. In order to address the wide range of possibilities that can be used when modelling tidal energy resources, an international standard has been developed by the International Electro-Technical Commission-Technical Committee 114 (IEC-TC114). The standard prescribes methods and procedures for determining, objectively and reliably, the scale and character of tidal energy resources in a region. The standard – Tidal Energy Resource Assessment and Characterization (62600-201:2015) provides a standardized methodology that ensures consistency and accuracy in the estimation, measurement, characterization and analysis of the theoretical tidal current resource at a selected location.

The standard specifies that the theoretical tidal energy resource is defined as the velocity probability distribution, which can be calculated either using hydrodynamic numerical models and/or measured data. The standard defines two distinct types of studies; feasibility (stage 1) and layout design (stage 2). A feasibility study focuses on an entire estuary or tidal channel with a medium level of uncertainty, while the layout design focuses on particular tidal energy sites in higher resolution which are selected based on the results of the feasibility study.

The standard recommendations can be divided in three main components: physical data requirements, model development and data analysis/results. Physical, or measured, data is required for model development and model calibration/validation. The required amount of data and its accuracy depends on the stage of the design, with the most important datasets being bathymetry, tidal height information and tidal currents. Other datasets such as meteorological, wave, stratification and other data can enhance the model validation and produce more physically accurate results. Minimum specifications are outlined for each study type, primarily grid resolution, number of modelled tidal constituents and type of model (2D or

3D). The model needs to be calibrated and validated by comparing model results to measured data. Once validated, a harmonic analysis is conducted on the model output to generate long-term model current predictions for a minimum period of one year. Harmonic analysis is most useful for the analysis and prediction of tide heights and tidal currents. Results from the tidal analysis are used to develop a histogram analysis for tidal current speed and direction and calculate the annual energy density (AE) and annual energy production (AEP) using Equations 1 and 2, respectively:

$$AE\ (Wh/m^2) = \sum_{i=1}^{N_h} \frac{1}{2}\rho U^3 \tag{1}$$

$$AEP(Wh) = AE\ C_d\ A \tag{2}$$

where C_d is the performance of the turbine, A $(m^2)$is the cross-sectional area of the turbine, N_h is the number of hours in the simulated year, ρ is the density of water (*1020 kg/m³*) and U (*m/s*) is the velocity. If the power curve is provided, the annual energy production can be estimated by combining the probability distribution of velocity and the power curve as indicated below:

$$AEP = \sum_{i=1}^{N_b} P_i(U_i) f_i(U_i) \tag{3}$$

where, N_b denotes the total number of velocity bins in the device power curve, $P_i(U_i)$ is the power in watts generated by the ith velocity bin of the tidal energy converter (TEC) power curve and $f_i(U_i)$ describes the proportion of time for which the mean current velocity has a value with the ith velocity bin of the TEC power curve.

This study applied the methodology prescribed by the standard to model available tidal energy throughout the Canadian Arctic coasts to determine potential tidal energy sites that may be of interest to renewable energy developers. More detail on methodology of the tidal resource assessment can found in the standard (62600-201:2015) – *Tidal Energy Resource Assessment and Characterization*. The study is based on **Stage 1** from the methodology defined in IEC (IEC 62600-201:2015) as shown in Table 1.

2. Model Development

The numerical model was developed using the TELEMAC system [15]: a suite of software tools for numerical modelling of free surface hydraulics, sediment, waves, in 1D, 2D or 3D. The Telemac System was originally created by the *Laboratoire national d'hydraulique et environment d'Électricité de France (EDF)* but is now managed by a consortium of core organizations under the OpenTelemac-MASCARET umbrella (www.openTelemac.org). The 2D free surface hydrodynamic model, TELEMAC-2D, was used to simulate the tidal heights and currents. The hydrodynamic model development consisted of: obtaining tide, bathymetric and shoreline datasets; creating a grid; specifying the boundary conditions; and, calibrating and validating the model using measured tidal height datasets. Tidal current stationary surveys, which provide a temporally evolving dataset of tidal currents at specific location, were not available in the Arctic. This type of data is normally used to validate the model tidal velocity at a specific location, usually near or at a proposed TEC site. There were, however, mobile surveys of tidal current speed which were analyzed as part of this study. It should be noted that a mobile survey, in itself, is not an adequate data source to specify an annual velocity distribution, but, used with model simulations, may be able to provide useful information about the spatial variability in tidal currents at a proposed TEC site.

Table 1: Tidal current energy resource assessment staging (IEC 62600-201:2015)

		Stage1	Stage2
Stage Characteristics	Aim	Feasibility	Layout Design
	Area	Whole estuary, channel	Development site
	Level of uncertainty	Medium	Low
Physical Data Requirements	Bathymetry	Match grid resolution	Match grid resolution
	Tidal Height	Match number of harmonic constituents	Match number of harmonic constituents
	Wave Characteristics/ Meteorological Data	Required if activated	Required if activated
	Flow Structure / Eddies / Turbulence Data / Stratification	Required if activated	Required if activated
	Tidal Currents	Required at site of interest	Required at site of interest
Modelling	Minimum number of harmonic constituents for modelling driving boundary	4-8	8-12
	Grid resolution at the area(s) of interest	<500 m > 10 grid cells across a channel section	<50 m
	Period of run	> 35 days	> 35 days
	Type	2D or 3D	3D
	Wind/Waves / Salinity Atmospheric Pressure / Turbulence / Sediment	Activate if necessary	Activate if necessary

2.1. Water level, bathymetry and tidal current datasets

Water level measurements are often combined with storm-surge – a phenomenon of rising/declining water levels associated with weather systems (i.e. atmospheric pressure, wind, waves, etc.) To remove the storm surge from the measurements, a harmonic analysis is performed on the water level to extract the astronomical tide: tidal levels result from gravitational effects of the earth, sun and moon. Harmonic constants are computed during the harmonic analysis which can be used to predict historical and future tides based on the position of the earth, sun and moon. The Canadian tidal constituent database, which contains the harmonic constants at each tide station around Canada, was obtained from the Canadian Hydrographic Service (CHS). For this study, 13 tide stations[1] were selected in or near the Arctic Archipelago as shown in Figure 1. The harmonic tidal height constants (amplitude and phase) at each station were compared to the modelled results. Any harmonic analysis (composing and decomposing) was computed using a python derivative of the IOS Tidal Package [16].

Bathymetry data was obtained from the Canadian Hydraulic Service (CHS) NONNA-100 Bathymetry Data [17] for the nearshore regions and the GEBCO_2020 Grid [18] for the deep ocean regions. The bathymetry data was interpolated to the models using the inverse distance weighted method. The location of the bathymetry measurements is shown in Appendix A at the four selected communities.

It should be noted that some bathymetry measurements downstream and upstream of Kuujjuaq were not available. The model bathymetry was interpolated using measured datasets to properly simulate the tidal flows in the river.

Mobile current velocity measurements was obtained from Acoustic Doppler Currently Profiler (ADCP) measurements that were collected by Quebec Ocean [19]. An ADCP instrument was attached to the hull of the CGCC Amundsen and the instrument acquired water velocity measurements as the ship travelled throughout the Arctic Archipelago and Hudson Bay. Guillot [19] processed the raw ADCP measurements and produced a dataset for each ship transect which consisted of two velocity components (u and v) divided into a number of different depth bins. In order to compare the measurements with model results, the velocity data was transform into depth averaged velocity. The resulting dataset is illustrated in Figure 2.

2.2. Datum

There is no accepted world standard definition of tidal datum or chart datum used for navigation charts and tidal height graphs. In this study, bathymetric depths and tide elevation were referenced to mean sea level.

[1] It should be noted that Cape Dorset and Gjoa Haven do not have tide stations, therefore a nearby station was selected during calibration and validation.

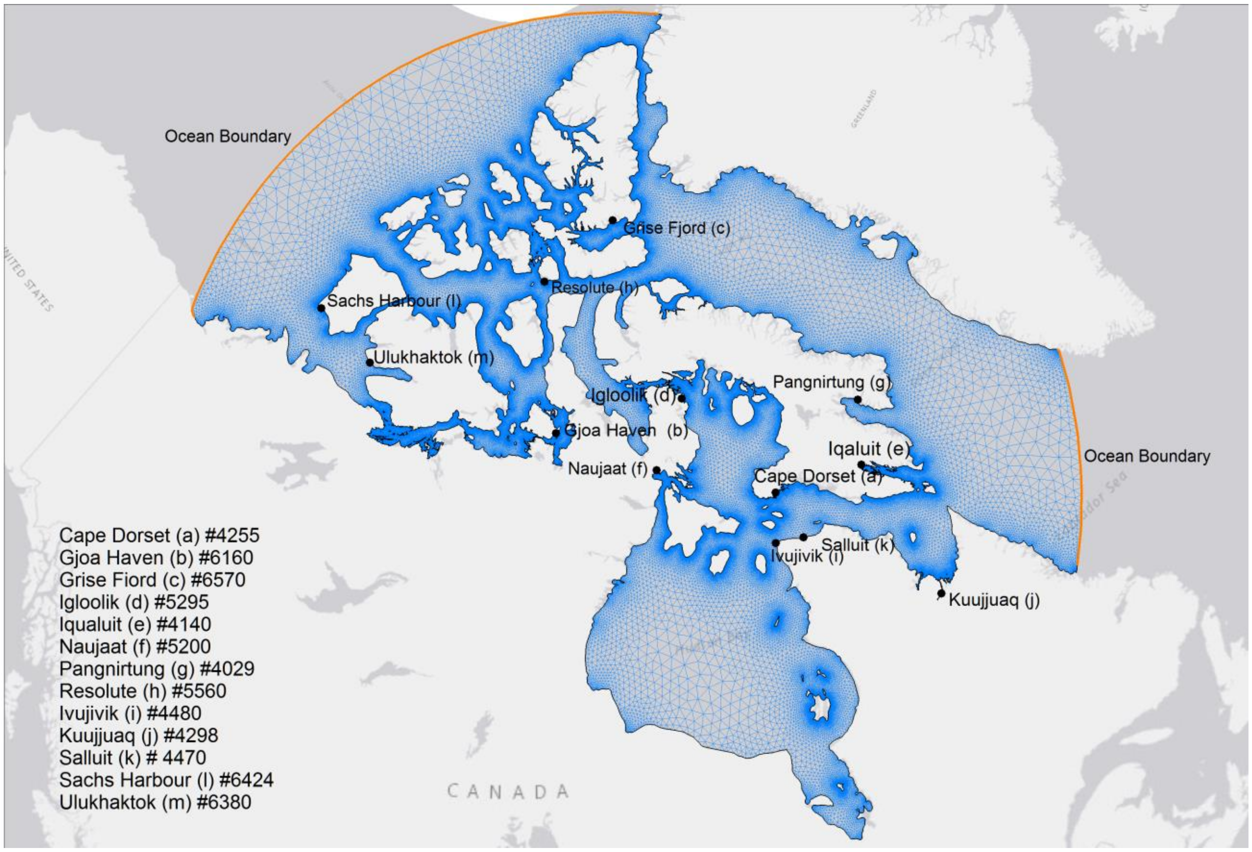

Figure 1: Unstructured grid, location of the ocean boundary and location of selected tide stations for the study.

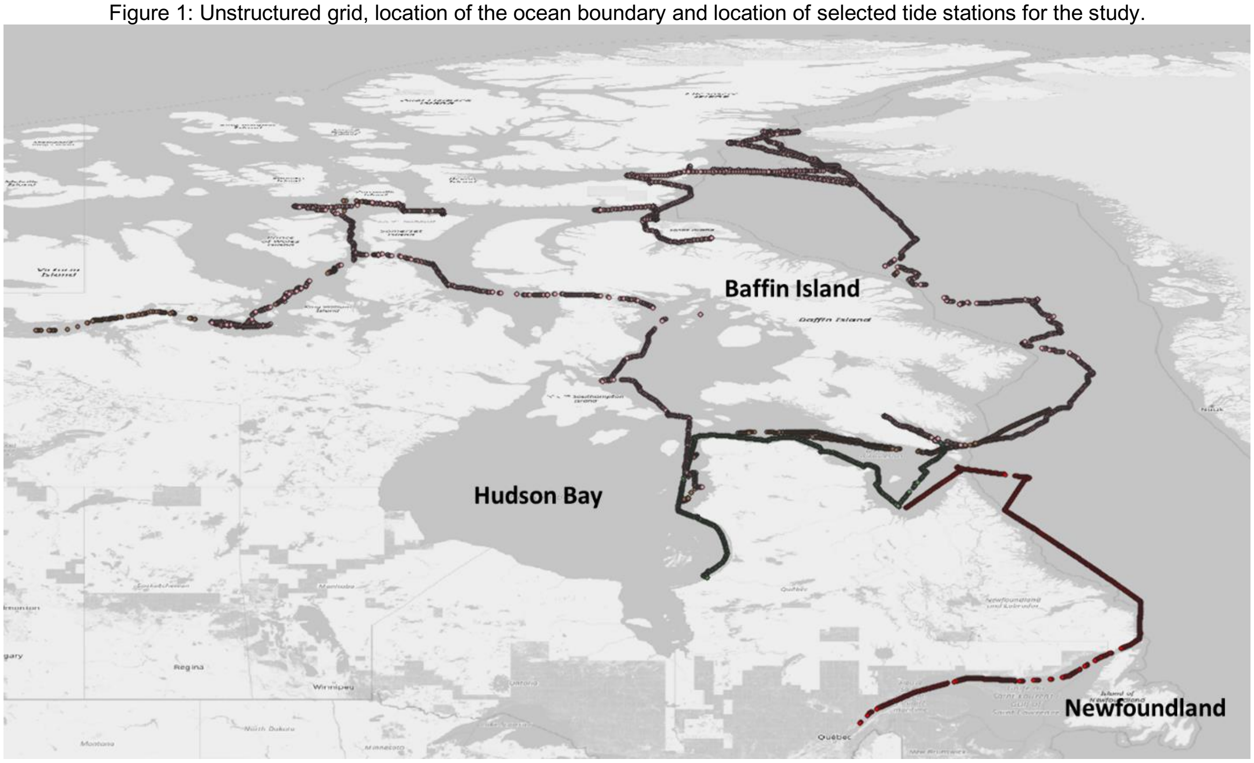

Figure 2. Processed ADCP transects.

2.3. Numerical model

The model requires a grid to discretize the physical system into a set of numerical triangular elements, often referred to as an unstructured grid. The unstructured grid allows the size of the elements to vary in space; where a fine grid allows proper representation in the model of certain fine details (i.e. shoreline areas), while a coarse grid is less accurate in the representation of these details (i.e. ocean areas), but results in a smaller number of elements thus requiring less computing time.

Different grids were generated with different resolution to assess the validity of the model. The grids were created using the finite element grid generator Gmsh [20]. The input files for Gmsh were created with Python, shoreline datasets from OpenStreetMap [21], and the bathymetric datasets from CHS [17]. Grid size was computed based on four criteria: location of interest, distance size, depth size and gradient size. Finer grid size was specified at the four locations of interest: Cape Dorset, Igloolik, Iqaluit and Kuujjuaq. The distance size was computed using the shortest fetch distance (i.e. shortest distance between two opposite shorelines): shorter distances (e.g. in bays and narrows) had finer grid size and longer distances (e.g. shorelines exposed to the ocean) had bigger grid size. The depth and gradients function sizes were computed using the bathymetric datasets: shallower depths and high gradient had finer grid size. Figure 1 shows the final grid that was used to validate the model and for the tidal resource assessment. The grid featured 764,300 nodes and 1,403,956 elements.

The model domain, as shown in Figure 1, covered the entire Arctic Coast of Canada mainly to accurately specify the tides at the ocean boundary (shown by the orange lines) and to properly simulate the tidal flows in the Arctic Archipelago. Astronomical tides were specified at the ocean boundary using the TPXO model [22] [23] - a global model of ocean tides. Thirteen harmonic constituents were used to force water level in the domain; eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf, Mm) and 3 non-linear (M4, MS4, MN4). Land boundaries were considered to be solid boundaries representing the shoreline. Energy flux was null at these boundaries and fresh water inflows were not accounted for in this study. Fresh water inflows can be added in future studies if it is believed that it could have an impact on the tidal resource assessment (i.e. Kuujjuaq).

TELEMAC-2D offers a variety of turbulence models of different complexity. The first involves using a constant viscosity coefficient. In this case, the coefficient represents the molecular viscosity, turbulent viscosity and dispersion. The second option involves an Elder model. The third option involves using a k-Epsilon model. This solves the transport equations for k (turbulent energy) and Epsilon (turbulent dissipation). The model equations are solved by a fractional step method, with convection of turbulent variables being processed at the same time as the hydrodynamic variables, and the other terms relating to the diffusion and production/dissipation of turbulent values being processed in a single step. Use of the k-Epsilon model also often requires a finer grid than the constant viscosity model and in this way increases computation time. The fourth option involves a Smagorinski model, generally used for maritime domains with large-scale eddy phenomena. The Smagorinski model was selected with a velocity diffusivity constant of 1.0E-5. Performing a sensitivity analysis between the turbulence models and coefficients is not required for Stage 1 as specified in the standard.

Coriolis forces were activated in TELEMAC-2D since it has a significant influence on large coastal domains, such as this study. The water density and gravity acceleration were set to 1,020 kg/m^3 and 9.81 m/s^2, respectively. The influences of wind, atmospheric pressure, ice, waves, flow stratification and sediments were not included in this stage of the study. Further research would be required to determine their impact on the tidal resource assessment.

2.4. Model Calibration and Validation

The hydrodynamic model was calibrated and validated by adjusting bottom friction parameters and grid resolution such that modelled tidal height resembled to the measured dataset. Most of the bottom friction was constant throughout the domain except in the area of Labrador Narrows and Frobisher Bay Islands. The grid was refined a few times during the calibration/validation process to accurately simulate the flow continuity in the Arctic Archipelago.

A minimum simulation time of 35 days is suggested in the standard to compute the AEP. However, this excludes any ramp-up or initialization period that the model requires to provide adequate results. A 7-day ramp-up was used to initialize the model before the 35-day simulation.

Figure 3 shows a Taylor diagram of the correlation of the harmonic amplitude of tidal height for each station. The lower-case letters corresponds to a station as shown in Figure 1. This was calculated by performing a harmonic decomposition analysis on the model results and then comparing it with the measured harmonic amplitude using the following constituents: M2, S2, N2, K1, O1, M4, M6, MK3, S4, and MN4. The optimum correlated value is located at a normalized standard deviation of 1.0, a RMSD of 0.0 and a correlation coefficient of 1.0 (red dot). The tidal heights were generally well correlated throughout the domain and below an RMSD value of 0.25 m. The model seems to slightly under-predict the tidal heights at Igloolik (point d) and Kuujjuaq (point j). This could be mitigated in a later stage of the study by refining the model grid, gathering additional bathymetry datasets near the site of interest and adjusting the bottom friction. Figure 4 shows the measured and modelled tidal heights at the four sites of interest (i.e. Cape Dorset, Igloolik, Iqaluit and Kuujjuaq). Overall, the model was able to accurately simulate the flow continuity and flow exchange in the Arctic Archipelago.

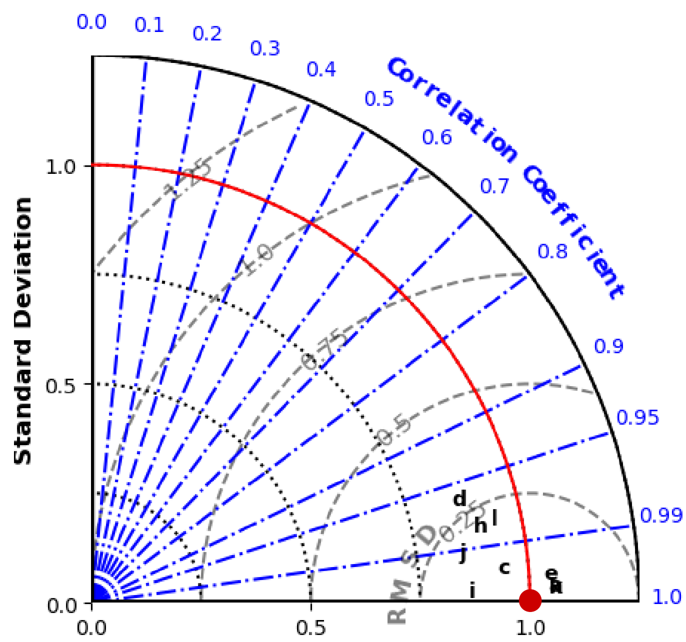

Figure 3: Taylor diagram of the correlation of the tidal height harmonic amplitude for each station.The lower-case letters corresponds to a station as shown in Figure 1. Well-correlated tidal height are near the correlation coefficient of 1.0 and a RMSD of 0.0 (red dot).

It should be noted that model calibration to tidal height ensures that the numerical model is able to accurately simulate flow continuity in the numerical domain. However, this procedure does not determine whether the model is capable of simulating local momentum/advection processes, which is important to accurately model tidal currents. It is recommended by the standard that simulated model currents are compared in detail to measured current data to evaluate the model's capabilities in this regard, and it is further recommended that the grid discretization (refinement) is adequate to replicate observed current conditions. Since the present study is not focused on any specific design location in the Arctic, and due to limited availability of stationary current measurements, the model was not calibrated/validated with current measurements.

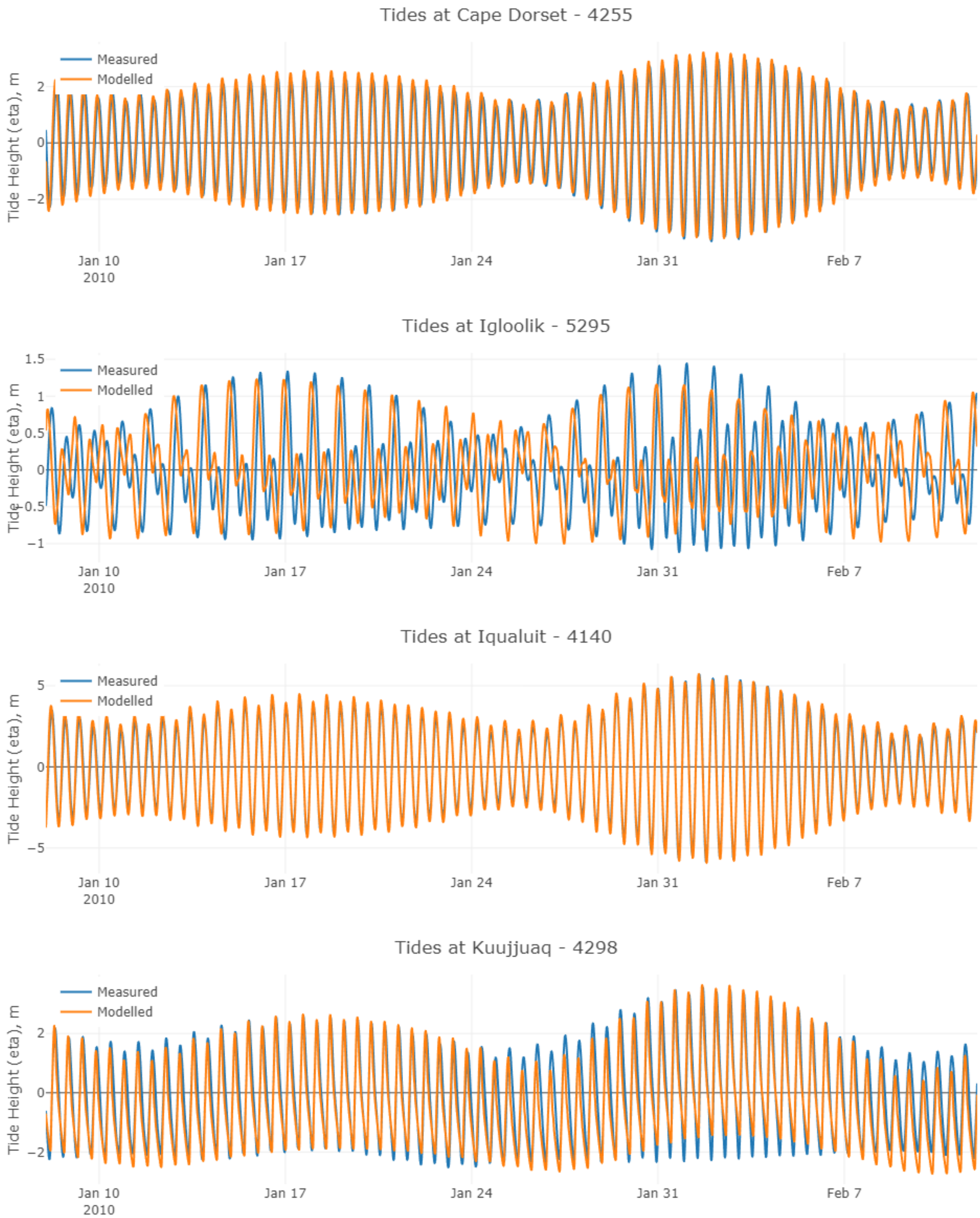

Figure 4: measured and modelled astronomical tides at Cape Dorset, Igloolik, Iqaluit and Kuujjuaq.

3. Tidal resource assessment

Tidal resource assessment (i.e. annual energy density, velocity probability, and annual energy production/demand) was analyzed at the four communities: Cape Dorset, Igloolik, Iqaluit and Kuujjuaq. As recommended by the standard, a harmonic analysis was conducted on the model output to generate long-term model current predictions for a period of one year. Results from the tidal analysis were used to develop a histogram analysis for tidal current speed and direction and to calculate the annual energy density and annual energy production.

3.1. Tidal Current Speed and Annual Energy Density

The annual energy density was computed using eq.1 throughout the model domain using model tidal current speed. Hotspots were identified by using a minimum threshold of 1.0 MWh/m^2 per year. Hotspots in regions without any measured bathymetry data were filtered out of the analysis. Figure 5 to Figure 8 show the annual density at the four selected communities. Appendix A shows the measured bathymetry at the four selected communities. All communities have hydrokinetic hotspots within a range of 50 km.

A histogram analysis for tidal current speed and direction was developed at 6 hotspots near the selected communities. The hotspot location and its distance from the community are shown in Table 2. Most of the hotpots have an average speed above 1.5 m/s as shown in Figure 9.

Table 2: Hotspot location at each selected community.

Community Name	Hotspot Location	Distance	Latitude	Longitude
Cape Dorset	South of Dorset Island	7 km	64.174	-76.476
Cape Dorset	N/S of Sakkiak Island	10 km	64.157	-76.564
Igloolik	Labrador Narrows	50 km	69.712	-82.586
Iqaluit	Frobisher Bay Islands	50 km	63.401	-67.948
Kuujjuaq	Near community	<5 km	58.112	-68.352
Kuujjuaq	River's Entrance	50 km	58.517	-68.175

3.1.1. Cape Dorset

The hotspot on the south side of Dorset Island, which is only 7 km from the community, has an average speed of 0.75 m/s, which is not ideal for tidal energy converters. Most tidal energy converters have a cut-in speed of 1.0 to 1.5 m/s, so it would generate energy less than 25% of the time. In addition, most tidal energy converters are designed and optimized for straight bi-directional tidal currents. This hotspot flows in a boomerang-like shape as shown in Figure 5, which can increase the amount of uncertainty in the efficiency of the turbine.

The other hotspots on the north and south side of Sakkiak Island, have an average speed of 1.5 m/s and maximum speed of 3.0 m/s. These hotspots are located 10 to 15 km from the community and have a total area of 3.0 km^2 of high hydrokinetic potential energy. It should be noted that bathymetry data does not exist in most of the channels around the islands around Cape Dorset. An elevation of -15 m was specified for most of these channels and might skew the results. Better bathymetry information would be needed for a better tidal resource assessment in this area.

3.1.2. Igloolik

The Labrador Narrows is a promising hydrodynamic energy site with an average speed of around 2.0 m/s and maximum speed of 5 m/s with little down time during slack tide. It has an area of 34.0 km^2 of high hydrokinetic potential energy and the hotspot is located 50-60 km from the Igloolik community. There is limited hydrokinetic energy within a few kilometers from the community.

3.1.3. Iqaluit

There is a limited amount of hydrokinetic energy near Iqaluit. However, there is a lot of hydrokinetic energy between the Frobisher Bay Islands, 50 to 100 km from Iqaluit. The average speed is around 1.0 to 1.5 m/s and the maximum speed is around 3.5 m/s. It has an area of 4.0 km^2 of high hydrokinetic potential energy.

3.1.4. Kuujjuaq

There is significant hydrokinetic energy (10-60 MWh/m^2 per year) along the Koksoak River: from the community of Kuujjuaq to the mouth of the river, 50 km away from the community. The average speed is around 1.75 m/s and the maximum speed is around 6.0 m/s. During the model simulation, river flow was not included and might affect the tidal current velocity during the flood tide during high discharge events.

Other processes such as stratification and horizontal density driven currents can have an impact of the tidal current speeds. High-speed flows can also carry a heavy load of sediment in suspension. Such heavy sediment loads, especially sand and gravel near the seabed, may significantly affect the fluid density, turbulence and friction in the flow, which may impact the design of the tidal energy converter. Further investigations into these processes would be recommended in a later design stage of the analysis.

3.2. Annual Energy Production and Demand

The annual energy production was computed using eq. 2 with an axial turbine of 6 m in diameter and with a general turbine efficiency of 0.35, or $C_d\ A = 10\ m^2$ without any cut-in and rated speed. This also assumes the turbine is producing energy for 8,760 hours per year. The annual energy demand at each community was obtained from Work Package 1. Results are shown in Table 3. An extra column was added to show the number of turbines required to meet the total annual energy demand per community.

Table 3: Annual Energy Production and Demand at the four selected communities.

Community Name	**Distance**	**Annual Energy Density**	**Annual Energy Production**	**Annual Energy Demand**	**# of turbines to meet demand[1]**
Cape Dorset	10 km	1-10 MWh/m^2	10-100 MWh	5,685 MWh	100 to 600
Igloolik	50 km	50-100 MWh/m^2	500-1,000 MWh	6,587 MWh	7 to 15
Iqaluit	50 km	10-30 MWh/m^2	100-300 MWh	59,140 MWh	200 to 600
Kuujjuaq	0-50 km	10-60 MWh/m^2	100-600 MWh	20,333 MWh	35 to 200

Note: 1) All hotspots have the capability of placing more than the number of turbines required to meet the annual energy demand.

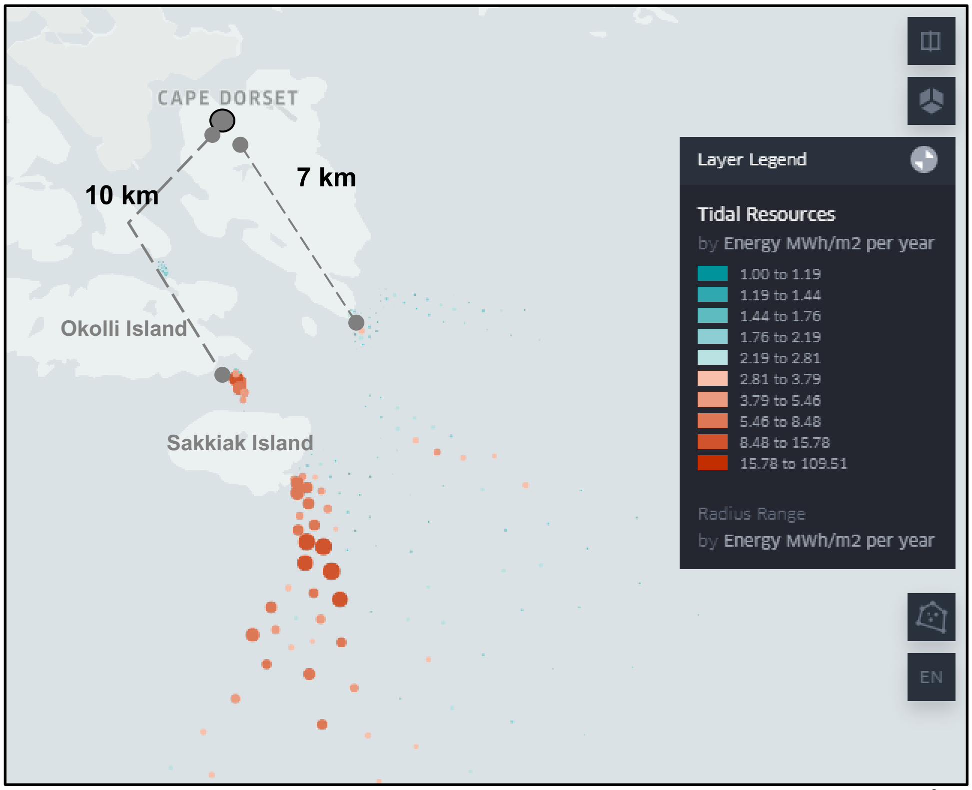

Figure 5: Annual energy density near Cape Dorset. Most of the hydrokinetic energy (5-10 MWh/m^2) is located on the north and south sides of Sakkiak Island. However, there is some energy (1-2 MWh/m^2) on the south shore of Dorset Island, approximately 7 km from Cape Dorset.

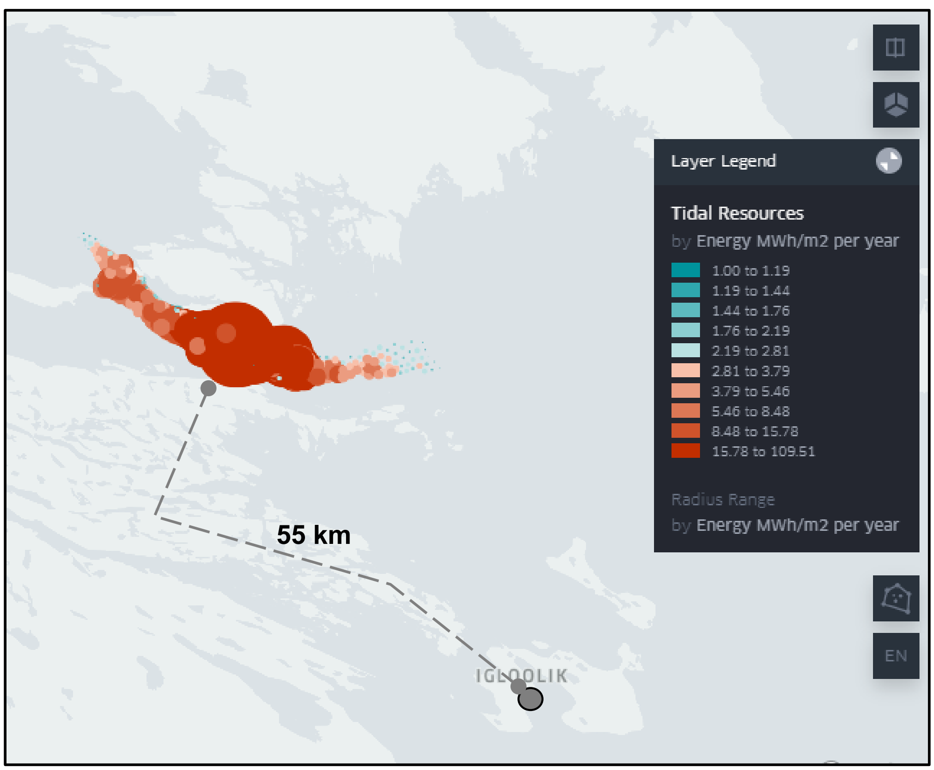

Figure 6: Annual energy density near Igloolik. There is significant hydrokinetic energy (50-100 MWh/m^2) in the Labrador Narrows, which is 50-60 km from the community. There is limited hydrokinetic energy near the community of Igloolik itself.

Figure 7: Annual energy density near Iqaluit. Most of the hydrokinetic energy (10-50 MWh/m^2) is located 50 km from the community between Frobisher Bay Islands. There is limited hydrokinetic energy near the community itself.

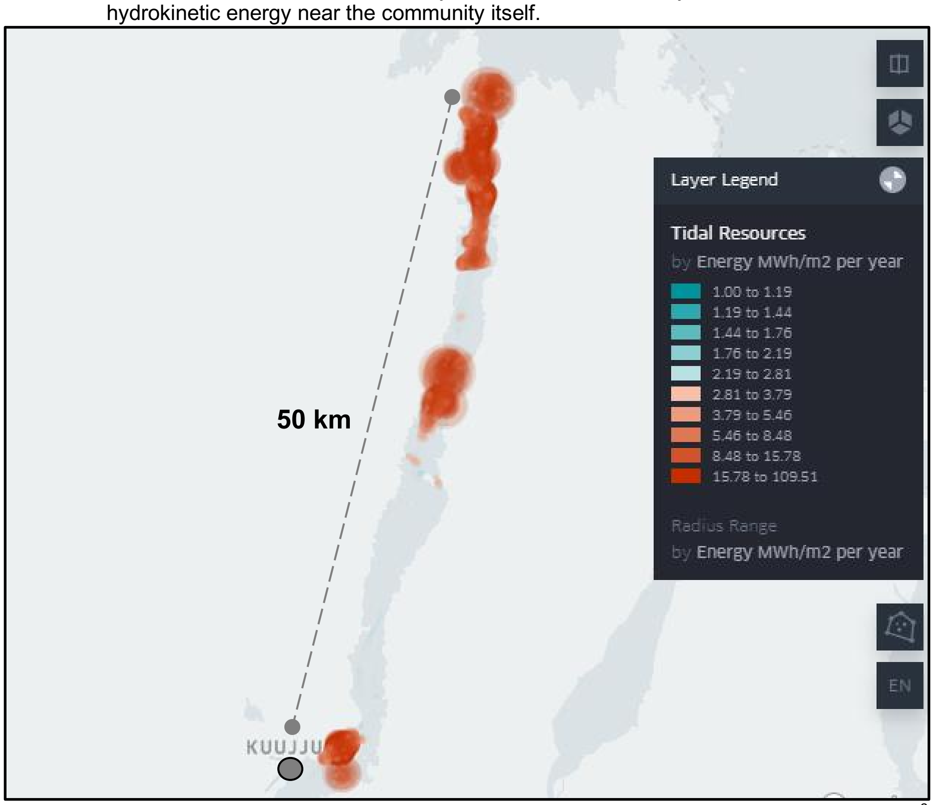

Figure 8: Annual energy near Kuujjuaq. There is significant hydrokinetic energy (10-60 MWh/m^2) along the river near Kuujjuaq and towards the river's mouth (50 km away from the community).

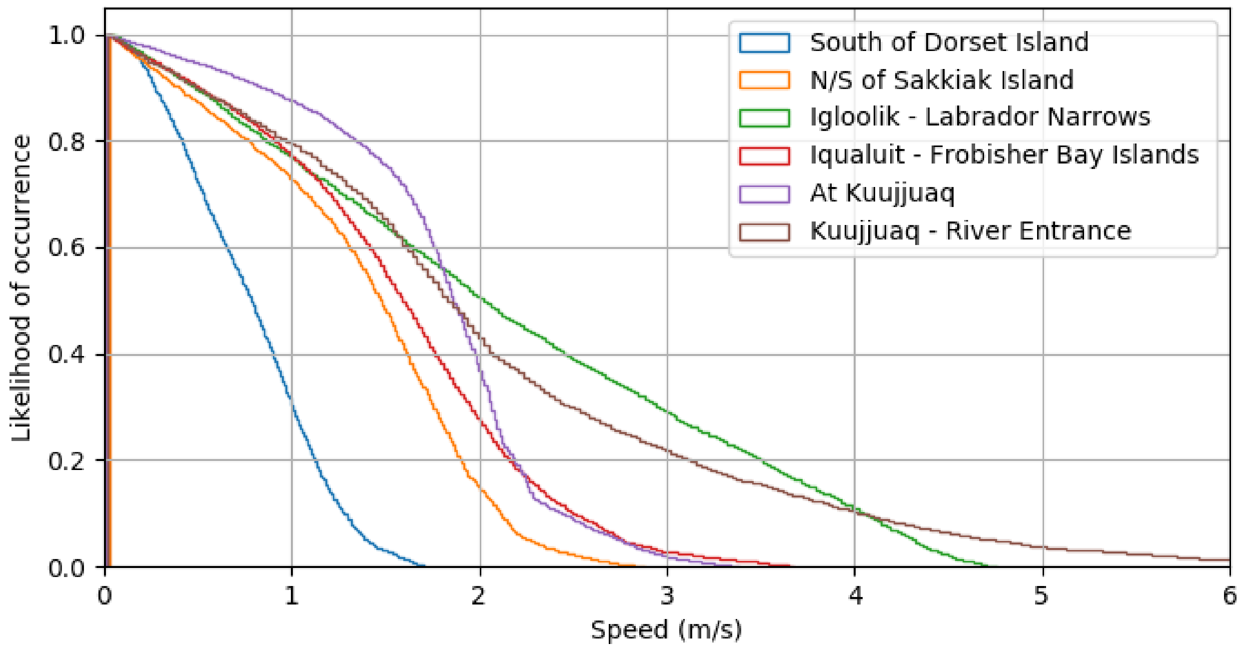

Figure 9: Exceedance probability of tidal current speed at the selected hotspot locations.

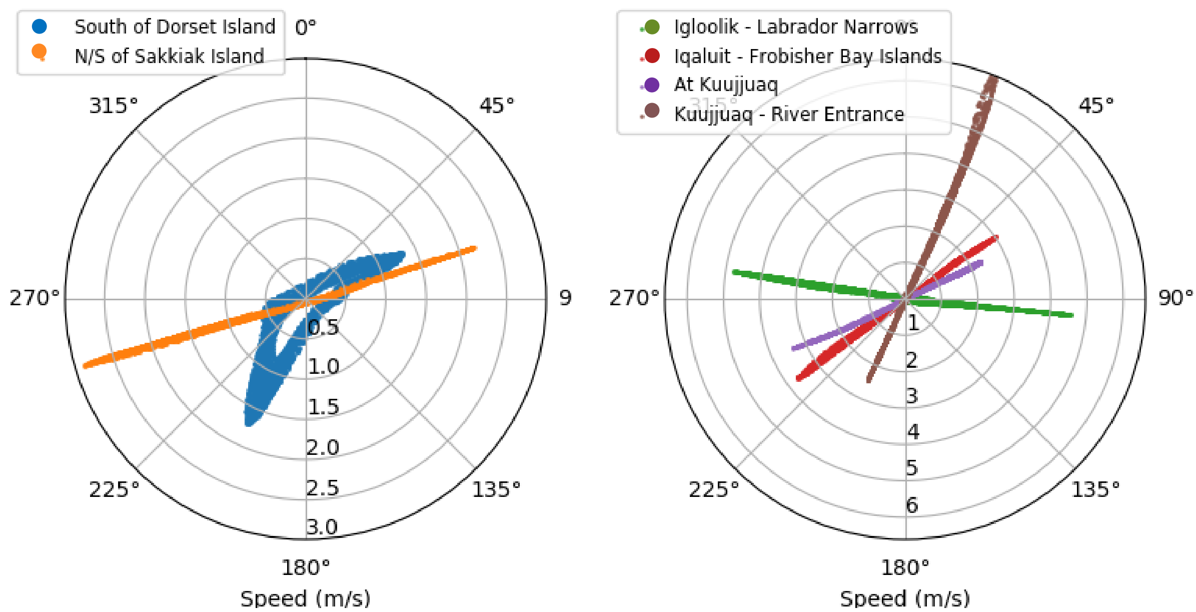

Figure 10: Tidal current direction at the selected hotspot locations.

3.3. Practice Resources and Other Characteristics

3.3.1. Ice seasons

All of the locations identified in this report are exposed to significant amounts of ice during the winter season. As shown in Figure 11 the mid-winter ice thicknesses in Cape Dorset and Kuujjuaq generally vary from 0.7 to 1.5 m which corresponds to a stage of development ranging from medium to thick first-year ice on the ice charts [24]. In Igloolik and Iqaluit many caps are observed at 1.5 m thickness which corresponds to 10 tenths, or complete coverage, of thick first-year ice. Ice thicknesses in Figure 11 which exceed 1.5 m indicate a significant presence of old ice. From the ice thickness data, it is observed that the presence of old ice at the Igloolik site has decreased considerably over the past 12 years. According to the ice charts, old ice is a possibility at all 6 locations identified in Table 2, however the polygons defined in a regional ice chart can be large which means that this analysis does not provide great spatial resolution. As a result, old ice may not be possible at the Kuujjuaq site near the community. Local residents may be able to provide greater insight on the risk of old ice at this specific location.

The ice freeze-up and break-up dates for each location were obtained from the Canadian Ice Service Ice Atlas (1981-2010) [25] and are shown in Table 4. There is ice present year round in Igloolik with a minimum in the ice extent at the end of the summer. According to the ice chart records, the freeze-up occurs in Iqaluit and Kuujjuaq in mid-November and in early December for Cape Dorset. The break-up occurs in Kuujjuaq and Cape Dorset in early and mid-June respectively and mid-July for Iqaluit.

Table 4: Canadian Ice Service Ice Atlas Freeze-up and Break-up dates (1981-2010).

Community	**Freeze-up**	**Break-up**
Cape Dorset	December 4	June 18
Igloolik	September 10 (minimal extent)	September 10 (minimal extent)
Iqaluit	November 19	July 16
Kuujjuaq	November 19	June 4

The Ice Atlas is 10 years old and incorporates data from the previous 30 years. For this reason, it is important to consider what impact climate change could have on those results. In Figure 12 the weekly ice concentrations are compared at two of the sites for the 30 years of the CIS Ice Atlas as well as the past 20 years. At both locations the reduction of overall ice cover is apparent; however a strong presence of ice remains throughout the winter season as evident from ice thicknesses in Figure 11 as well. The reduction of ice cover is apparent throughout the season at the Igloolik site and appears to be more focused on the end of the season at the Iqaluit site. The time of the break-up appears unchanged at the two locations however the freeze-up is occurring one week later in Igloolik and 1-2 weeks later in Iqaluit.

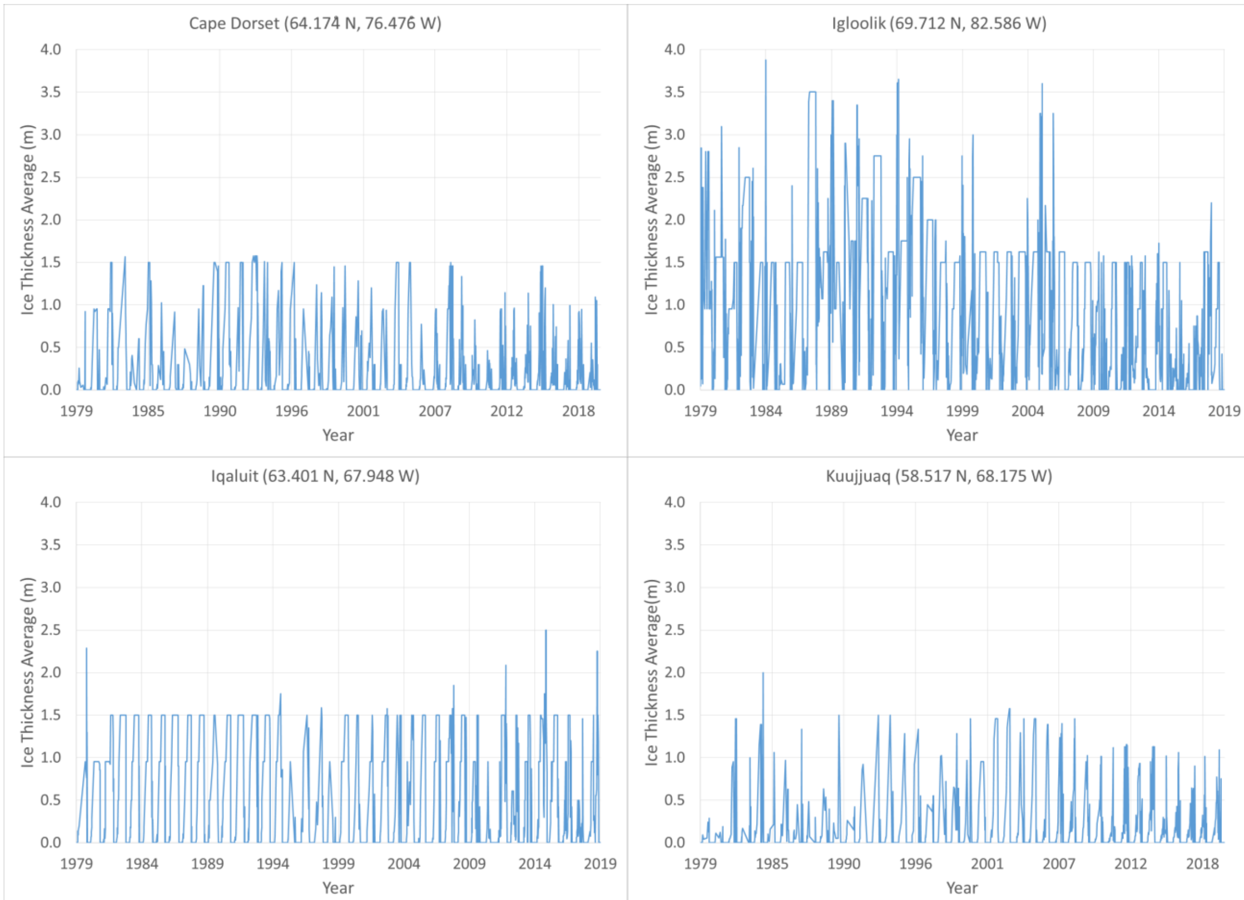

Figure 11: Average ice thicknesses at the Cape Dorset, Igloolik, Iqaluit and Kuujjuaq sites taken from the Canadian Ice Service Regional Ice Charts (1979-2019).

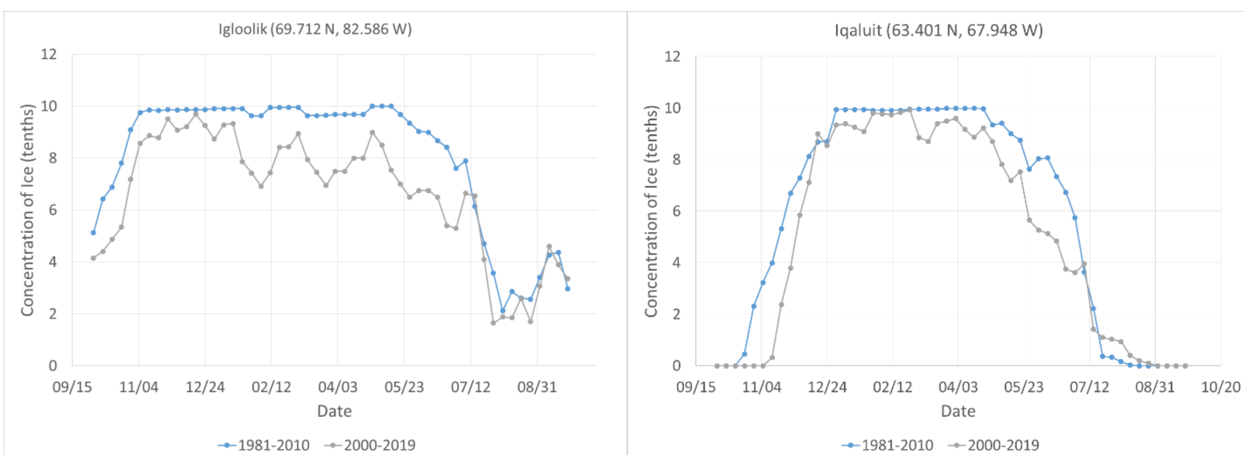

Figure 12: Weekly ice concentration data from the Igloolik and Iqaluit sites taken from the Canadian Ice Service Regional Ice Charts (1981-2019).

A sharp decrease in temperature over turbulent waters without the presence of an ice cover can result in the generation of frazil ice when combined with wind. It is believed that all of these locations would be susceptible to frazil ice generation near the water surface. There is limited information available on the impacts of frazil ice generation on the operation or integrity of hydrokinetic turbines [26] [27]; however it has been shown to produce strain on other infrastructure. Installing turbines at deeper water depths can reduce the risks related to interaction with both frazil ice and ice cover.

The authors of this report have not found sufficient information on ice islands or icebergs at the identified sites to assess the risks that those ice features could pose to a hydrokinetic turbine. Local communities may be able to help to assess if this is a risk.

3.3.2. Ice debris

Hydrokinetic turbine devices deployed in rivers, estuaries or coastal waters are exposed to many hazards that can degrade their operational performance and viability. Harmful interactions with debris and ice debris, either floating or submerged, are one such hazard that can have serious and costly consequences. Tyler [28] reports that the potential for dangerous interactions with debris are a leading consideration when evaluating potential sites for deployment of hydrokinetic power systems. The probability of encountering ice, and the type of ice encountered, varies widely from one place to another and depends on the characteristics of the deployment site and the details of the turbine system. Turbines suspended from floating platforms are vulnerable to impacts by ice floating at or near the surface, while bottom-mounted systems are less vulnerable. The likelihood that interaction with ice debris will produce damage or degrade turbine performance is in large part dependent on whether the turbine system has been engineered with debris mitigation in mind. To be considered successful, debris mitigation devices or systems must prevent harmful debris interactions with the turbine rotor and/or its support structure without diminishing the speed of the flow incident to the turbine rotor.

3.3.3. Vertical velocity variation, turbulence and water density

A 2D hydrodynamic model only resolves depth-averaged velocities and does not resolve vertical velocity variations in the water column. In Stage 2, once a proposed site has been selected, 3D modelling is required to accurately resolve the tidal currents at the TEC location in the water column. Typically, for open water, the flow velocity tends to be higher near the water surface and limited near the bottom. For ice-covered conditions, high flow velocity tends to shift towards the middle of the water column. As for turbulence, an irregular motion of the water resulting from eddies and vertical currents, it is not currently known what scale, frequency and magnitude of current variability are important, nor are the limits of hydrodynamic and CFD modelling used for turbine design. This is a subject of ongoing research.

The variation of seawater density and freshwater density from the Koksoak River can have a minor impact on the available energy resource in the water column. A 3D model or a stationary tidal current survey using a current profiler at the proposed site is recommended to determine the impact of fresh water on tidal current velocity.

3.3.4. Geomorphology, sediments and seabed material

Determining the bathymetry and seabed material at the proposed site is key to determine the type of mooring to be employed, as well as possible soiling issues that devices could face. High-speed tidal flows may carry a heavy load of sediment in suspension. Such heavy sediment loads, especially sand and gravel near the seabed, may significantly affect the fluid density, turbulence and friction in the flow, which may impact the set-up and performance of the proposal device, and the integrity of anchoring structures [29]. If high sediment loads are suspected, as in the case of the Koksoak River, further investigations are recommended using sediment traps or similar methods.

3.3.5. Hydrokinetic device and turbine mounting arrangement

Hydrokinetic turbines are classified into two categories: axial-flow turbines and cross-flow turbines. Axial-flow turbines have a rotational axis parallel or inclined to the direction of water flow. These turbines are similar to wind turbines and may have two, three, or more blades on the rotor. The rotor of these turbines is disk type. The application of these turbines is preferred in marine and ocean environments since it requires enough depth to accommodate the turbine. Cross-flow turbines have a rotational axis perpendicular to the direction of water flow. The rotors of these turbines are cylindrical in shape and therefore utilize the space in a more efficient manner than do axial-flow turbines. Cross-flow turbines can be place horizontally or vertically (depth-wise).

There are three different types of mounting options: bottom structure mounting (BSM), near-surface structure mounting (NSM), and floating structure mounting (FSM), which can all accommodate axial-flow and cross-flow turbines. There are strengths and weaknesses for all three options but for the northern communities, the BSM turbines seems to be the better option, mainly to avoid ice debris, ice cover and frazil ice. There are many challenges related to BSM in cold conditions and the following key aspects needs to be considered:

- The flow velocity tends to be higher near the water surface for open water condition and in the middle of the water column for ice covered condition. Depending on the proposed TEC site, depth are typically 10-50m and would need a gravity based structure to reach 5 to 25m in height to maximize power efficiency.
- Placement and maintenance are very difficult for BSM turbines since the structure is under water. Underwater generator and sea cable are also required for BSM, which tends to increase the complexity of the design. A hybrid BSM and FSM design approach, such as ORPC design [30], is a possible solution to mitigate some the maintenance challenges.

4. Conclusion

The NRC-OCRE has developed a numerical model to perform a tidal hydrokinetic energy resource assessment near four northern communities: Cape Dorset, Igloolik, Iqaluit and Kuujjuaq. The numerical model was developed using the methodology proposed in the International Electro Commission standard: Tidal Energy Resource Assessment and Characterization (62600-201:2015). The standardized methodology ensures consistency and accuracy in the estimation, measurement, characterization and analysis of the theoretical tidal current resource assessment. The feasibility study or stage 1 methodology was used to develop and validate the model, and to calculate the annual energy density, velocity probability distribution and annual energy production. Other characteristics that impact the tidal resource assessment, such as ice cover, ice debris, vertical velocity variation, sediments and mounting arrangement were also discussed.

Hotspots were identified at all four northern communities and are summarized below:

- **Cape Dorset**: There are few hotspots around the community. The closest hotpot is on the south side of Dorset Island, which is only 7 km from the community, and has an average speed of 0.75 m/s or 1 MW/m^2 per year, which is not ideal for tidal energy converters. Most tidal energy converters have a cut-in speed of 1.0 to 1.5 m/s, so it would generate energy less than 25% of the time. The other hotspots are located on the north and south sides of Sakkiak Island: it has average speed of 1.5 m/s with maximum speed of 3.0 m/s or an annual power density of 10 MWh/m^2 per year. These hotspots are located 10 to 15 km from the community and have a total area of 3.0 km^2 of high hydrokinetic potential energy. Depth at these hotspots varies from 30 to 50 m. The ice season is usually 7 months of the year.

- **Igloolik**: There are no hotpots near the community itself. The Labrador Narrows, 50 km from the community, is the closest hotpot and contains significant hydrokinetic energy. The average speed is around 2.0 m/s with maximum speed of 5 m/s with little down time during slack tide. It has an area of 34.0 km^2 of high hydrokinetic potential energy, averaging 75 MWh/m^2 per year. However, depths vary from 50 to 100 m with limited shallow areas to deploy, operate and maintain bottom structure turbine mounting. A surface mounting turbine is not recommended since the water near Igloolik is covered in ice 10 to 12 months a year. There is currently ice coverage data for the Labrador Narrows but there is a high probability of ice sheets or ice debris year round.
- **Iqaluit**: There is a limited amount of hydrokinetic energy near Iqaluit. However, there is significant hydrokinetic energy between the Frobisher Bay Islands, 50 to 100 km from Iqaluit. The average speed ranges from 1.0 to 1.5 m/s with a maximum speed of 3.5 m/s. The annual power density is 20 MWh/m^2 per year. It has an area of 4.0 km^2 of high hydrokinetic potential energy and depths varying from 10 to 50 m suitable for bottom mounting turbines. The ice season is around 8 months from mid-November to mid-July. Although it was not investigated as part of this study, a tidal barrage near the Iqaluit community in Burton Bay or Tarr Inlet might be feasible. A tidal barrage is a power station that generates electricity from the natural rise and fall of the tides. It works by capturing a large volume of water behind a man-made structure which is then released to drive turbines and generate electricity. The tidal range in Iqaluit varies from 6 to 8 m.
- **Kuujjuaq:** There is significant hydrokinetic energy (10-60 MWh/m^2 per year) along the Koksoak River: from the Kuujjuaq community to the mouth of the river (50 km away from the community). The average speed is around 1.75 m/s with maximum speed of around 6.0 m/s. Other processes such as stratification and horizontal density driven currents, due to river flow, can have an impact on the tidal current speeds. Depths vary from 5 to 30 m which is suitable for bottom mounting turbines. On average, the ice season is 8 months of the year from mid-November to mid-July. The Ocean Renewable Power Company (ORPC) — a private tidal developer — is already considering an in-stream turbine deployment near the mouth of the Koksoak River.

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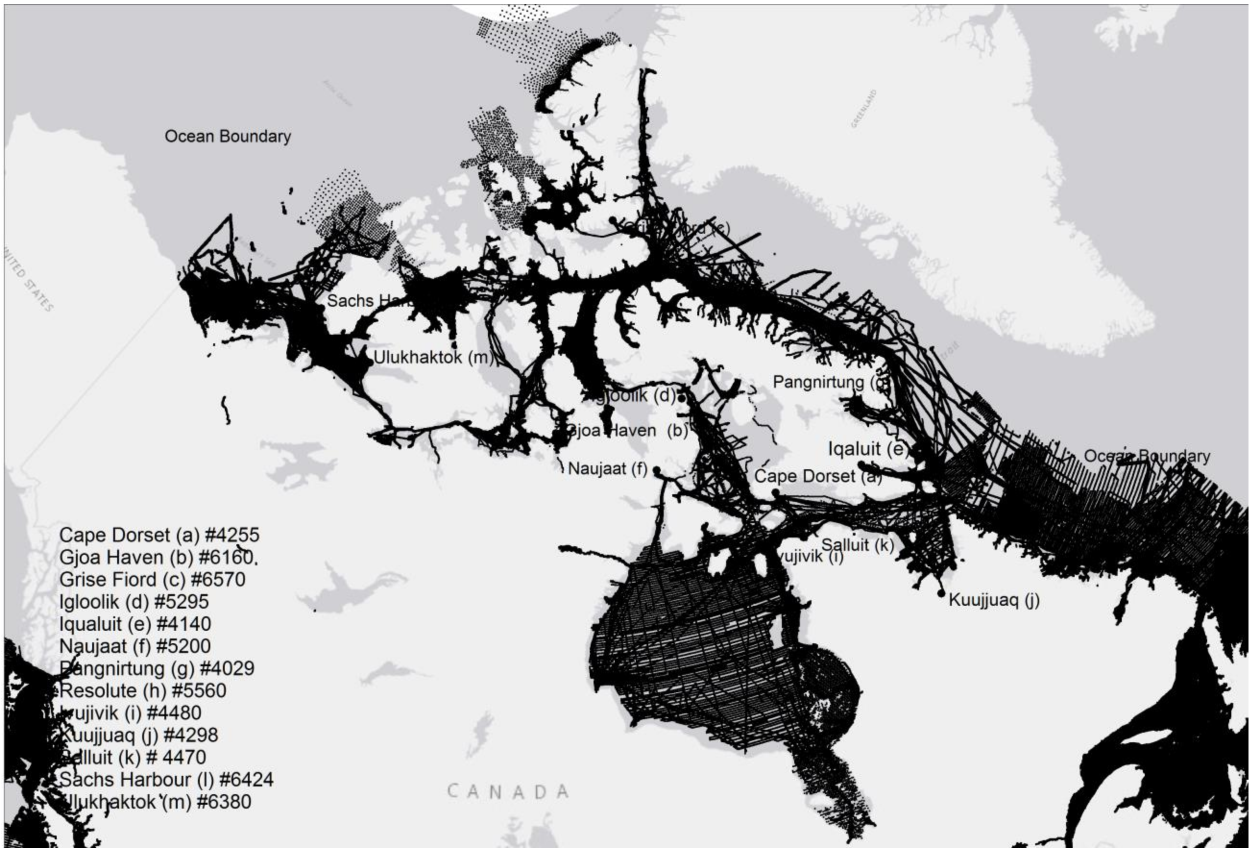
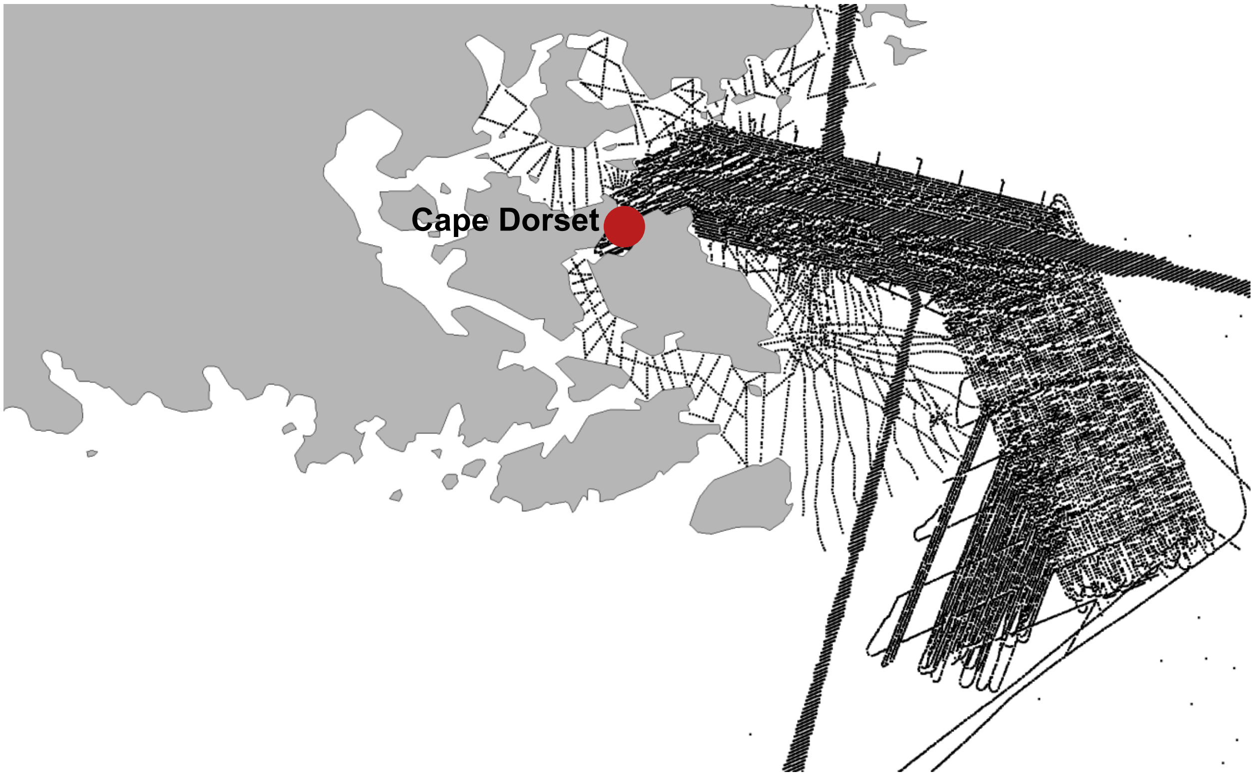
Appendix A – CHS NONNA-100 Bathymetry

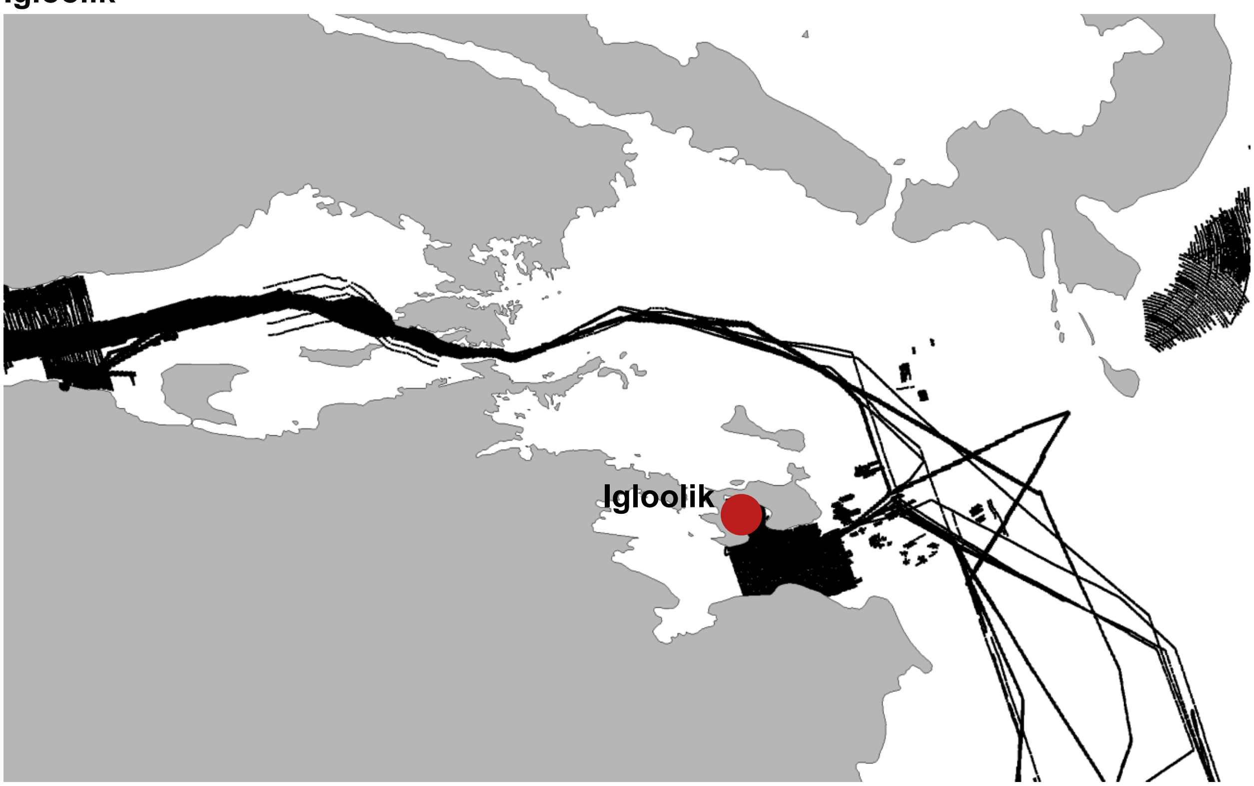
Arctic Region



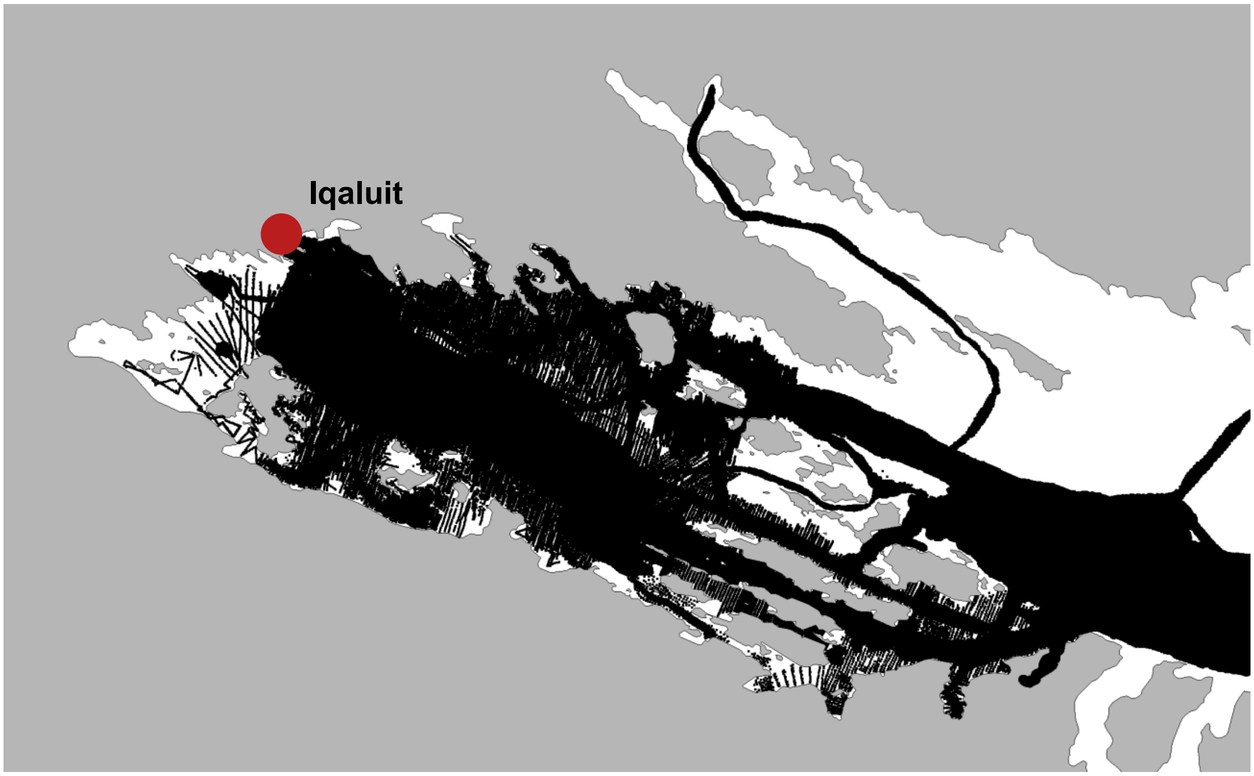
Cape Dorset



Igloolik



Iqaluit



Kuujjuaq