Distribution of beluga in western Hudson Bay with respect to estuary habitat characteristics and vessel traffic

by

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Abstract

Western Hudson Bay is undergoing habitat changes associated with increased anthropogenic activities including vessel traffic from shipping and whale watching ecotourism. These river estuaries are habitat for the Western Hudson Bay (WHB) beluga whale, the largest know beluga population. This thesis addresses two important questions, which environmental conditions contribute to critical beluga habitat in the western Hudson Bay, and what is the response of beluga to tourism vessel traffic in the Churchill River estuary. Beluga were identified in nadir imagery from a 2018 summer aerial survey of the Nelson, Churchill and Seal River estuaries, and oblique images taken of the Churchill River estuary in August 2020. The location of beluga within each survey area was modeled with respect to remotely sensed environmental data. Beluga habitat use was found to be associated with rivers as well as the concentration of total suspended sediments, and colored dissolved organic matter. Using environmental characteristics, a previously unidentified important habitat unit for beluga was discovered in the Knife River estuary. Distance measurements between belugas and tourist vessels were obtained from oblique images using trigonometric equations and georeferencing points taken in the Churchill River estuary. Through distance analysis, it was found that beluga showed attraction to kayaks, avoidance to paddleboards, and independence from motorboats and Zodiacs. Results from this thesis should inform management decisions for the WHB beluga population, including the establishment of a National Marine Protected Area which is currently under consideration.

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I dedicate my thesis to my goddaughter Rosalie Ausen.

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Contribution of Authors:

Chapter 2:

Emma Ausen, Marianne Marcoux, David Walker, and David Barber contributed to the conceptualization and design of the study. Laura Dalman and David Barber collected photographs. Emma Ausen reviewed the photos. Emma Ausen and Atreya Basu compiled satellite data. Atreya Basu calibrated equations for TSS, and CDOM. Yens Ehn and Atreya Basu developed the method for determining river plume boundaries. Atreya Basu and Emma Ausen determined the river plume boundaries for the Churchill, Seal and Knife rivers. David Walker and Emma Ausen ran the MDA. Emma Ausen ran RSF, cross validation, and sensitivity analysis. Emma Ausen wrote the first draft of the manuscript. Marianne Marcoux and David Barber supervised the project. All authors contributed to manuscript revision, read and approved the submitted version. David Barber and Marianne Marcoux funded the project.

Chapter 3:

Emma Ausen, Marianne Marcoux and David Barber contributed to the conceptualization and design of the study. Emma Ausen collected data, reviewed photos, and developed the equations for distance measurements. Emma Ausen and Wayne Chan explored oblique photo measurements, and calibrated distance measurement equations. Emma Ausen wrote the first draft of the manuscript. Marianne Marcoux and David Barber supervised the project. All authors contributed to manuscript revision, read and approved the submitted version. David Barber and Marianne Marcoux funded the project.

1 Chapter 1: Introduction

The Churchill, Seal, and Nelson estuaries are summer habitat for the Western Hudson Bay (WHB) beluga whale (*Delphinapterus leucus*) population, one of Manitoba's most valuable ecotourism resources. This population is culturally significant to Inuit and Cree Peoples, who harvest WHB beluga (Hoover et al., 2013; Tyrrell, 2007). The interactive behavior of belugas in the Churchill estuary is unique to the area, and a major draw for ecotourism to the region (Malcolm & Penner, 2011). In 2021, the Committee on the Status of Endangered Wildlife in Canada categorized WHB belugas as not at risk, though threats to population health have included risks from increased shipping traffic into Hudson Bay, anthropogenic noise pollution, and changes to river flow from hydrologic activity (COSEWIC, 2004, 2020). Though the WHB beluga population is the largest known population, they are understudied, especially with regards to habitat use and anthropogenic impacts on habitat. The western Hudson Bay is being assessed for the establishment of a National Marine Conservation Area (NMCA) due to its high cultural and ecological significance. A greater understanding of the relationship between WHB belugas, their habitat, ecotourism, and shipping traffic is required for improved site-specific population management.

1.1 Arctic development

Anthropogenic presence in the Arctic is changing. Challenges that traditionally came with Arctic access have decreased due to the ice melting impact of climate warming. The Arctic is becoming increasingly easy to access for human activities related to development and tourism. Earlier onset of ice melt and later ice freeze up allows for an expansion of the shipping season, and greater access to Arctic waters (J. Dawson et al., 2018; Pizzolato et al., 2014; Reeves et al., 2014). The reduction in overall ice cover and advances in technology for drilling has resulted in the greater potential for hydrocarbon extraction (Chvileva, 2020; Ebinger & Zambetakis, 2009). Tourism is becoming more prevalent in the Arctic, with cruise ships and private charter boats that bring people to a remote place where they can see marine mammal species and explore regions that most of the world is unable to access (Lemelin et al., 2010; Manley et al., 2017; Saarinen & Varnajot, 2019).

The Hudson Bay is an Arctic and a subarctic inland sea spanning Manitoba, Nunavut, Ontario, and Quebec. The Hudson Bay is habitat for many marine mammals, fish species, sea birds species and home for communities that are located along the shore where people can access resources from the bay (McDonald, M. Arragutainaq, L. Novalinga, 1997). Industrial and anthropogenic development in the Hudson Bay includes hydrological changes to river systems, and the development of the Arctic Bridge shipping vessel path that exports resources from Churchill, Manitoba (J. Dawson et al., 2018; A. J. Smith et al., 2017). An ecotourism industry in the western Hudson Bay has become important for the local economy of Churchill, Manitoba, as visitors from around the world come to see polar bears, beluga whales and the unique environment (Malcolm & Penner, 2011; The Churchill Beluga Whale Tour Operators Association et al., 2015).

1.2 Study site and species: The Western Hudson Bay beluga population

Beluga whales (*Delphinapterus leucas*) are migratory, circumpolar odontocetes whose habitat includes areas in the Canadian Arctic (COSEWIC, 2004). Beluga are philopatric, meaning they return to the same areas and follow the same migratory routes every year (Caron & Smith, 1990; Colbeck et al., 2013). Of the 21 or more known beluga populations or stocks, 8 migrate through or occupy North America year-round (COSEWIC, 2004, 2020; DFO, 2018; Lowry et al., 2017). The Western Hudson Bay (WHB) beluga population returns to the west coast of Hudson Bay every summer, with high concentrations of beluga in the Churchill, Seal and Nelson estuaries (COSEWIC, 2020). Aerial survey sampling of WHB summer habitat has given population estimates between 50,000 and 60,000 belugas (Matthews et al., 2017; Pierre R Richard, 2005). Altered estuary habitat use by beluga in the western Hudson Bay includes changed Nelson River and Churchill River flow from hydrologic activity, and a beluga population decline in the Churchill estuary attributed to hunting pressure from a commercial fishery in the early 1900's (Finley et al., 1982; Hansen, 1988; Idle, 1989; Newbury et al., 1984; Pierre R. Richard, 1993; Sergeant & Brodie, 1975). The collapse of the commercial fishery and the 1979 ban on sport hunting resulted in belugas returning to the Churchill estuary (COSEWIC, 2004; Doan & Douglas, 1953; Sergeant & Brodie, 1975). WHB belugas continue to be sustainably harvested by Nunavut and Nunavik Inuit, with around 300 belugas taken per year (COSEWIC, 2004; Matthews et al., 2017). Industrial development has an overlap with beluga populations in the Arctic including shipping (Hauser et al., 2018; McWhinnie et al., 2018; Pirotta et al., 2018), resource extraction (Reeves et al., 2014), construction (Kendall et al., 2013), and tourism (J. Dawson et al., 2018; Halliday et al., 2018; Johnston et al., 2017). Reeves et a. (2014)

determined that 9-12% of beluga habitat in the Arctic overlapped with current or future oil and gas leased areas. These anthropogenic activities risk beluga population health through degradation of habitat and noise pollution which has been shown to impact beluga through reduced communication abilities and altered behavior (Finley et al., 1990; Gomez et al., 2016; Lesage et al., 1999; Scheifele et al., 2005; Small et al., 2017).

Observations and satellite tags have been used to reveal the routes and timing of WHB beluga migration, which can vary based on environmental conditions such as sea surface temperature (Bailleul et al. 2012a, Eastern Hudson Bay beluga population). Migratory routes are learned from cultural inheritance from maternal lineages, taught as young belugas remain with their mothers for the first two years, and migrate with closely related pods (Colbeck et al., 2013; Turgeon et al., 2012). Belugas are present at the mouth of the Churchill River when ice breaks up in mid-June, and leave estuaries for their wintering ground in the Hudson strait by mid-September (Doan & Douglas, 1953; Hansen, 1988; Idle, 1989; Sergeant, 1973; Sergeant & Brodie, 1969b; A. J. Smith et al., 2017). While WHB belugas are philopatric to the summer estuaries in the western Hudson Bay they do not have site fidelity to a specific estuary (Colbeck et al., 2013; Doan & Douglas, 1953).

DNA tested from Churchill River belugas was found to have a lower haplotype diversity than other Hudson Bay populations, due to high concentrations of haplotype H02 and H05, which indicates WHB belugas are a separate population (de March & Maiers, 2001; de March & Postma, 2003; Turgeon et al., 2012). Turgeon et al. (2012) used mitochondrial DNA (mtDNA) to show that WHB belugas are a genetically distinct population. Hudson Bay belugas show little genetic differences at nuclear loci (nDNA) and there is high genetic overlap, which indicates interbreeding in the Hudson Strait wintering ground (de March & Maiers, 2001; de March & Postma, 2003; Turgeon et al., 2012). Homogeneity in mtDNA samples from WHB beluga whales further supports conclusions that this population is philopatric, and returns to the estuaries along the western Hudson Bay every summer (Brennin et al., 1997; Brown Gladden et al., 1997; de March & Maiers, 2001; de March & Postma, 2003).

As climate change results in increased temperatures, the WHB beluga habitat is changing. Temperature driven distribution changes of beluga prey species may have negative consequences. Capelin (*Mallotus villosus*), an important prey species for beluga, could respond to an increase in temperature of 2-4°C by a shift in distribution between 4 and 18 degrees further north in the western Hudson Bay (Doan & Douglas, 1953; Kelley et al., 2010; Sergeant & Brodie, 1975; Watts & Draper, 1986). Ice break-up and water temperature shifts are believed to trigger summer migration and affects timing of beluga arrival to estuaries. Shifts in timing of ice breakup could lead to altered migratory timing, which could result in an earlier arrival to the estuary and increased entrapment risks in unpredictable ice distribution along migratory routes (Bailleul et al., 2012b; Hauser, Laidre, Stafford, et al., 2017; O'Corry-Crowe et al., 2016). Decreases in sea ice have been linked to the increased presence of killer whales in the Hudson Bay (S. H. Ferguson et al., 2010; Higdon & Ferguson, 2009). Estuaries may become crucial sanctuary habitat for beluga as killer whales expand their range. Trophic cascades and the spread of viral diseases has increased for marine mammal species stemming from the reduction in sea ice, and WHB beluga are susceptible to these effects (Grebmeier et al., 2006; VanWormer et al., 2019).

1.3 Estuary habitat use

In the western Hudson Bay, areas with high abundance of beluga whales are located around the estuaries of the Churchill, Seal, and Nelson rivers (Matthews et al., 2017; Richard et al., 1990; Pierre R Richard, 2005; Sergeant, 1973). Beluga estuary distribution is connected to tide, with individuals following high tide upriver, and low tide downriver and away from the shore (Caron & Smith, 1990; Doan & Douglas, 1953; Hansen, 1988; V V Krasnova et al., 2012). This same pattern was observed in aerial surveys of the Churchill river found congregations beluga in southern end of the estuary during high tide and fewer beluga present in the estuary during low tide (Idle, 1989). Beluga have also been observed moving in an out of the Nelson river estuary with the tide, with higher use by belugas during high tide (R. Baker, 1989; A. J. Smith et al., 2017). Beluga distribution in an out of estuaries is also related to differential water temperatures between the estuary and surrounding waters, wind conditions which impact the sea state, and storm conditions (Doan & Douglas, 1953; Hansen, 1988; Idle, 1989).

Estuary habitat use by belugas is not fully understood, but there are multiple potential benefits. Habitat modeling has been used to describe beluga distribution in relation to habitat features that are beneficial for growth and survival. Beluga may make the long migratory journey from winter habitat in the Hudson strait to reach rich in prey summer estuaries (Doan & Douglas, 1953; Sergeant & Brodie, 1975; Watts & Draper, 1986). Remotely sensed chlorophyll a concertation is a method to describe primary production, nutrient availability through turbidity, and prey availability, that has been linked to beluga distribution in the Beaufort Sea (Frey et al., 2017; Hornby et al., 2017). River flow plays an important role in distribution of prey, generating nutrient availability through upwelling and a freshwater saltwater mixing zone that result in higher productivity and prey (A. J. Smith et al., 2017). In the Nelson estuary, belugas were located on average 12 km further from the Nelson river mouth when the flow from the river was higher (A. J. Smith et al., 2017). Beluga in the Beaufort Sea were shown to be associated with turbid waters (Hornby et al., 2016). In Cook Inlet, Alaska the river flow, coastline composition, and prey distribution are factors that are related to habitat use by beluga (Goetz et al., 2007, 2012). Warmer waters in estuaries has been theorized to be beneficial for the growth of calves and juvenile beluga (Hansen, 1988; Sergeant & Brodie, 1975; A. J. Smith, 2007). Belugas may also be migrating to estuaries because the warm freshwater from estuaries can assist in molting (St. Aubin et al., 1990). Shallow estuary waters provide predator protection from killer whales (*Orcinus orca*), who cannot swim in shallow depths (Matthews et al., 2017; Pierre R Richard, 2005; Westdal et al., 2016). Bathymetry, slope and substrate type have all been shown to be related to beluga presence in estuaries and open water habitat (Asselin et al., 2011; Barber et al., 2001; Goetz et al., 2012; Hornby et al., 2017; Moore, DeMaster, et al., 2000).

1.4 Interaction with vessels

=Increased shipping traffic into the Port of Churchill is likely as warming temperatures allow for greater access to the Arctic Ocean (J. Dawson et al., 2018; Reeves et al., 2014). While the risk for boat collision with beluga in the Churchill estuary is low, noise from shipping vessels may mask, or prevent the detection of beluga calls through overlapping frequency and high decibels (Clark et al., 2009; C. Erbe & Farmer, 1998; Christine Erbe, 2008; Gervaise et al., 2012; Pirotta et al., 2018). In response to increased acoustic noise, beluga have been observed fleeing, altering call characteristics, altering behavior, and have increased stress levels (Bakhchina et al., 2017; Finley et al., 1990; Finneran, 2015; Gomez et al., 2016; Kendall & Cornick, 2016; Lyamin et al., 2011; Popov et al., 2013, 2016; Scheifele et al., 2005). Avoidance behavior by beluga in the Churchill estuary could negatively impact the ecotourism industry.

Through interactive behavior with tourist vessels, including investigating kayaks and swimming alongside zodiacs, beluga in the Churchill estuary are a major draw for ecotourism to the region (Malcolm & Penner, 2011). It is important to assess the degree to which these small boats effect beluga. Decisions of tour operators in whale watching industries are directly related to the threat and disturbance levels to whales (Anwar et al., 2007). Observations of beluga in the Churchill estuary revealed that greater than 150m away from boats there is an increase in feeding behavior, which could suggest that tourist boats disrupt feeding (Malcolm & Penner, 2011). Vessel traffic has been shown to disrupt feeding patterns of killer whales along the Pacific coast (David Lusseau et al., 2009; Williams et al., 2006a). Humpback whales, killer whales, and fin whales have been observed to alter their behavior in response to tour boat presence with directional changes, differences in rates of surfacing, change in dive time, and by fleeing the area (Edds & Macfarlane, 1987; Scheidat et al., 2004; Williams et al., 2002). This response depended on the quantity of tourist boats (Williams et al., 2002). Belugas in the St. Lawrence river estuary responded to ecotourism boats with avoidance behavior, grouping of beluga, increased speed, movement, and interactions with boats (Blane & Jaakson, 1994). In the White Sea, Russia, beluga responded to tourists boats presence in gathering areas with behaviors such as fleeing or diving to hide (Vera V. Krasnova et al., 2020). The proportion of fleeing or diving behaviors decreased over time, which could indicate habituation to boat presence (Vera V. Krasnova et al., 2020). Impacts to beluga from ecotourism include noise disturbance, as small boats create acoustic noise at frequencies that overlap with the calls of beluga whales, which results in call masking (Lesage et al., 1999). In the Churchill River estuary there is some evidence that beluga may be habituated to tourist boat presence (Malcolm & Penner, 2011). Management currently in effect includes a 100 meter approach distance for boats to belugas along the western Hudson Bay, and a 50 meter approach distance for the beluga in the Churchill and Seal estuaries (*Regulations Amending the Marine Mammal Regulations. SOR/2018-126*, 2018).

1.5 Analysis techniques

1.5.1 Habitat modeling

Habitat modeling has been used to describe beluga distribution in relation to their habitat across North America (Asselin et al., 2011; Bailleul et al., 2012b; Barber et al., 2001; Goetz et al., 2007, 2012; Hauser, Laidre, Stern, et al., 2017; Hornby et al., 2016, 2017; Loseto et al., 2006; Moore, DeMaster, et al., 2000). Locations of individuals are used in habitat modeling to describe what habitat is selected. The use of habitat more than would be expected given a random distribution shows that an individual has selected this habitat (D. H. Johnson, 1980). Habitat modeling is limited to the environmental data available. Habitat characteristics identified in

North America that are related to beluga distribution include ice cover characteristics, bathymetry, surface chlorophyll a concentration, turbidity, sea surface temperatures, substrate type shelf characteristics, slope and distance from biological and environmental features including rivers, prey types and tidal flats (Asselin et al., 2011; Bailleul et al., 2012b; Barber et al., 2001; Goetz et al., 2007, 2012; Hauser, Laidre, Stern, et al., 2017; Hornby et al., 2016, 2017; Loseto et al., 2006; Moore, DeMaster, et al., 2000). Group size, sex and age class are factors that differentiate habitat use by beluga (Goetz et al., 2007; Loseto et al., 2006; P R Richard et al., 2001; A. J. Smith et al., 2017). There are few examples of habitat modeling completed on Hudson Bay belugas. Eastern Hudson Bay belugas were found to be associated with colder water temperatures in their summer habitat (Bailleul et al., 2012b). Habitat use by beluga in the western Hudson Bay estuaries has been examined through observations of beluga grouping, movement, and hunting (Hansen, 1988; Idle, 1989; Sergeant & Brodie, 1975). The distribution of beluga in the Nelson river estuary was modeled in relation to river outflow changes from hydrological activity, showing increased river flow resulted in a shift in average beluga location around 12 km further from shore (A. J. Smith, 2007; A. J. Smith et al., 2017).

1.5.2 Remote sensing

Remote sensing is the use of optical or thermal sensors to scan the earth's surface. In cloud free areas, satellite imagery can be processed to obtain environmental characteristics of the earth's surface and waters including surface chlorophyll a concentration and sea surface temperatures (Richards, 2013). The availability of satellite data is expanding as 10 m resolution data is available from Sentinel 2 worldwide without cost, and high-resolution imagery can be purchased and tasked for specific areas. With higher availability comes more opportunity to make use of images to investigate oceanographic conditions. Through calibration of equations with water quality samples, ocean surface sampling using remote sensing has resulted in the ability to estimate water quality indicators using remotely sensed bands. This has included calculation of total suspended sediments and colored dissolved organic matter (Doxaran et al., 2005; Nechad et al., 2010).

1.5.3 Photogrammetry

Image captures and video recordings are a method of remote sensing that can be used in combination with photogrammetry methods to measure environmental features. Photographic aerial surveys are used for marine mammal population estimates and habitat analysis through captures of individuals seen near the water's surface (M. C. Ferguson et al., 2018; Pierre R Richard, 2005). Oblique photos show the landscape at an angle that includes the horizon, and these photos have been used to asses physical characteristics of the environment including tracking glacial calving, river discharge and snow processes (Cassotto et al., 2015; Danielson & Sharp, 2013; Garvelmann et al., 2013; Young et al., 2015). Oblique camera systems have also been used in wildlife monitoring with motion triggered cameras or a time-lapse system, which takes photos at a designated interval (Cutler & Swann, 1999). There have been few examples of the use of a time-lapse photographic system for monitoring of marine mammals, but there are many advantages. Time-lapse cameras can monitor weather conditions and anthropogenic activities, have the ability to identify age class of individual whales, are low cost, can record for long periods of time, and are simple to set up (Merchant et al., 2014; Rayment et al., 2018). The use of time-lapse systems in combination with acoustic underwater recording devices has proven beneficial for identification of unknown sounds in marine environments (Merchant et al., 2014). Detection rates of whales was similar when comparing a hydrophone to a time-lapse camera in the same area (Rayment et al., 2018). Camera time-lapse systems show potential to be useful for assessing marine mammals response to human activities along the coast (Paiva et al., 2015).

During observational behavior studies of whales, location and movement patterns have been described using triangulation, estimation of distances, and the use of a theodolite (Blane & Jaakson, 1994; Connor et al., 2000; Malcolm & Penner, 2011; Scheidat et al., 2004; Whitehead, Moorman, Wainstein, et al., 2010). Through the use of camera measurements including height, angle, and focal length, and the surface characteristics, the location of pixels within a photo may be identified (Höhle, 2008; Paiva et al., 2015; Whitehead, Moorman, Wainstein, et al., 2010). The measurement of real life objects using images relies on the photogrammetric collinearity equation, which assumes that there is a straight line between the object in real life, the center of the camera image, and the location of the object on the image (Whitehead, Moorman, Wainstein, et al., 2010). Error sources need to be considered with photogrammetric measurements. Error can arise from lens distortion, uncertainty in measurements of the camera, and errors in digitization of images (Burnett et al., 2019; Christiansen et al., 2016; S. M. Dawson et al., 2017). Corrections for these errors can include the use of models to estimate the source of error, sensitivity analysis, calibration of the camera in advance using a grid system, and accounting for error by using control points as methods to calculate differences between captured and real life points (Burnett et al., 2019; Christiansen et al., 2016; S. M. Dawson et al., 2017; Paiva et al., 2015). The conditions of sea state, precipitation and glare should be considered with regards to the probability of detection of a marine mammal in an image (Aniceto et al., 2018; Paiva et al., 2015; Rayment et al., 2018).

1.6 Thesis objectives

The goal of this research is to investigate beluga habitat use in the western Hudson Bay using advances in geospatial analysis techniques, photogrammetry, and remotely sensed data. This research includes the following two studies:

1. Modeling of belugas in the Western Hudson Bay to investigate river influenced summer habitat distribution.
2. Investigate beluga response to tourism vessels in the Churchill River estuary using a simple time-lapse camera system.

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2 Chapter 2: River Influenced Beluga Summer Habitat Use in Western Hudson Bay

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2.1 Abstract

Advances in the collection of marine environmental characteristics using satellite imagery can be used to increase understanding on marine mammal habitat distribution. The Churchill, Seal, and Nelson estuaries are high occurrence summer habitat areas for the Western Hudson Bay (WHB) beluga whale (*Delphinapterus leucus*) population. Western Hudson Bay area is under consideration for the establishment of a marine protected area (MPA). Beluga summer estuary use has been connected to prey availability from freshwater-saltwater plumes, and warm water thermal or molting advantages. Beluga locations were identified using aerial photographs collected from western Hudson Bay estuaries in summer 2018. To investigate habitat use, environmental characteristics related to water quality were calculated from Sentinel 2 bands and used to outline river plume boundaries in the Seal, Knife and Churchill areas. Multiple discriminant analysis (MDA) was used to differentiate between habitat areas according to their environmental characteristics including distance to intertidal areas, distance to shore, sea surface temperature, concentration of total suspended sediments (TSS), and concentration of colored dissolved organic matter (CDOM). The Nelson River, Churchill River estuary, Churchill offshore, Seal River, and Knife River were identified as distinct habitat areas. Resource selection functions and model selection (BIC) was used to determine which environmental variables were important for beluga habitat selection. In each habitat area the final model included water quality variables (TSS, CDOM) and the distance to the river mouth or river plume. Results from this analysis, including identification of preferred habitat and habitat areas should be considered in future management decisions including the establishment of a MPA.

2.2 Introduction

Beluga whales are an endemic Arctic and Subarctic species that occupy waters around Canada, Russia, Greenland and the US state of Alaska (Lowry et al., 2017). While some beluga populations are year-round residents, many populations migrate between winter and summer habitats. Beluga are often found in coastal waters during the summer or along ice-edges in winter, with combinations of these habitats during migration (Asselin et al., 2011; Bailleul et al., 2012a; Barber et al., 2001; Hauser, Laidre, Stern, et al., 2017; Moore, DeMaster, et al., 2000). Habitat studies have found relationships between beluga distribution and ice cover characteristics, bathymetry, surface chlorophyll a concentration, water turbidity, sea surface temperature, substrate type, shelf characteristics, slope and distance from biological and environmental features including rivers, prey areas and tidal flats (Moore et al. 2000; Barber et al. 2001; Loseto et al. 2006; Goetz et al. 2007, 2012; Asselin et al. 2011; Bailleul et al. 2012b; Hornby et al. 2016, 2017; Hauser et al. 2017b). Migratory populations often return to river estuaries in the summer following the breakup of river ice (Bailleul et al., 2012b; Doan & Douglas, 1953; Hauser, Laidre, Stafford, et al., 2017; O'Corry-Crowe et al., 2016).

The use of summer estuary habitat occurs in multiple beluga populations. Beluga whale estuary occupation has been hypothesized to be related to matrilineally learned philopatry, biological advantages associated with greater prey availability, optimal habitat for molting, predator protection, or a combination of these factors (Finley, 1982; Sergeant, 1973; Sergeant & Brodie, 1969a; A. J. Smith, 2007; St. Aubin et al., 1990). In the Mackenzie estuary lower coastal water temperatures were associated with belugas moving further into the estuary likely to reach warmer waters (Scharffenberg et al., 2019). Warm estuary freshwater has been linked to increasing skin temperature for molting or energy efficient epidermal growth (Aubin et al., 1990; Watts et al., 1991). In Cook Inlet, Alaska, beluga were found to be associated with mudflats or tidal flats, which may indicate habitat use for bottom rubbing behavior associated with molting (Goetz et al., 2007, 2012). As estuary occupation occurs across beluga populations, further investigation into the environmental drivers of beluga distribution in estuaries would contribute to greater understanding of critical summer habitat.

The WHB beluga population is the largest known, with an estimated size of 54,473 individuals based on summer aerial surveys (Matthews et al., 2017; Richard, 2005). The summer range of this beluga population has been recorded as extending between Northern Ontario and

Nunavut, with high concentrations of belugas identified in the Nelson, Churchill and Seal river estuaries between June and September (Matthews et al., 2017; Richard et al., 1990; Pierre R Richard, 2005; Sergeant, 1973). While the WHB belugas are philopatric to the summer estuaries in western Hudson Bay they do not have site fidelity to a specific estuary (Colbeck et al., 2013; Doan & Douglas, 1953). Investigations of WHB beluga summer habitat use include observations of beluga feeding on capelin in the Churchill River, beluga movement to shallow waters to avoid killer whales along the Seal River estuary, and associations with warmer water temperatures (Watts et al., 1991; Watts & Draper, 1986; Westdal et al., 2016). In the Nelson River estuary, belugas were found to be located further from the Nelson River mouth in years when river flow was higher, suggesting the freshwater saltwater mixing zone is an important determinant of beluga distribution (A. J. Smith et al., 2017). Hansen (1998) observed that higher river flow in the Churchill River may have explained differences in beluga estuary distribution, including a more widespread distribution and reduced upper estuary occupation (Hansen 1988). Beluga habitat areas in western Hudson Bay are under assessment for the establishment of a National Marine Conservation Area (NMCA) due to its high cultural and ecological significance.

Advances in environmental data collection using satellite remote sensing can be used to increase understanding on habitat distribution. In this paper, beluga locations from a 2018 aerial survey were used with environmental characteristics to differentiate between habitat areas using multiple discriminant analysis (MDA) and quantify habitat use using resource selection functions (RSF). Satellite data was used investigate beluga distribution in high occurrence areas of western Hudson Bay with respect to river estuary characteristics including total suspended sediment concentration, colored dissolved organic matter concentration, and river plume delineation. Habitat characteristics related to estuary use theories are also investigated, including distance to intertidal areas, sea surface temperature, and distance to shore.

2.3 Study site

Western Hudson Bay is characterized by semidiurnal tides (R. Baker, 1989; R. F. Baker et al., 1994; Wang et al., 2012) which along with estuary shape and river flow impact the location of the river plume and freshwater saltwater mixing zones. Large tides contribute to intertidal zones or mudflats that extend along western Hudson Bay coastline and contribute to high sediment content in the estuary and coastal waters. The Churchill estuary is enclosed and stratified, with a river plume that can extend up to 4km from the estuary mouth during low tide

(R. F. Baker et al., 1994). The Nelson estuary is an open estuary surrounded by tidal flats and mudflats with homogeneous mixing of freshwater and saltwater due to tides, high winds, and shallow waters (R. F. Baker et al., 1993). Both the Nelson and the Churchill estuaries have been found to be sources of nutrients including dissolved organic carbon (DOC) and silica, while surrounding marine waters are sources of phosphorus (R. F. Baker et al., 1993, 1994; Granskog et al., 2007; Mundy et al., 2010). Flow from the Churchill River was diverted to the Nelson in 1976 to increase hydroelectric capabilities, which resulted in a 75-95% decrease in flow from the Churchill, and the potential that anthropogenic regulation of flooding through the dams reduced sediment transport to the Nelson estuary (R. F. Baker et al., 1994; Duboc et al., 2017; Manitoba Wildlands, 2005; Newbury et al., 1984). The average flow from the Nelson, Churchill and Seal rivers is 2050 m^3/s, 600 m^3/s, and 361 m^3/s respectively (Déry et al. 2011, Duboc et al. 2017), and the Nelson River is the largest contributor of freshwater to the Hudson Bay (Déry et al. 2005).

2.4 Methods

2.4.1 Aerial survey information

A helicopter aerial photographic survey was flown in the Nelson, Seal and Churchill River estuaries, areas where high numbers of beluga whales occur (Figure 1). Photos collected along these surveys were georeferenced using helicopter track log information, ExifTool (ExifTool Version 11.48, https://exiftool.org/, accessed 3 Jun 2019), R (R 3.6.1, https://cran.r-project.org/, accessed 3 Jun 2019) and ArcGIS 10.6. Beluga captures in these photos were recorded as a point shapefile in ArcMap. Beluga identified where classified by pod using the 'chain rule' to create groups (Connor et al., 2000). A beluga that is less than 1 body lengths distance from another beluga was determined to be part of that group or pod (Connor et al., 2000; Lemieux Lefebvre et al., 2018). For each group the location was calculated as the mean center between all beluga in the group.

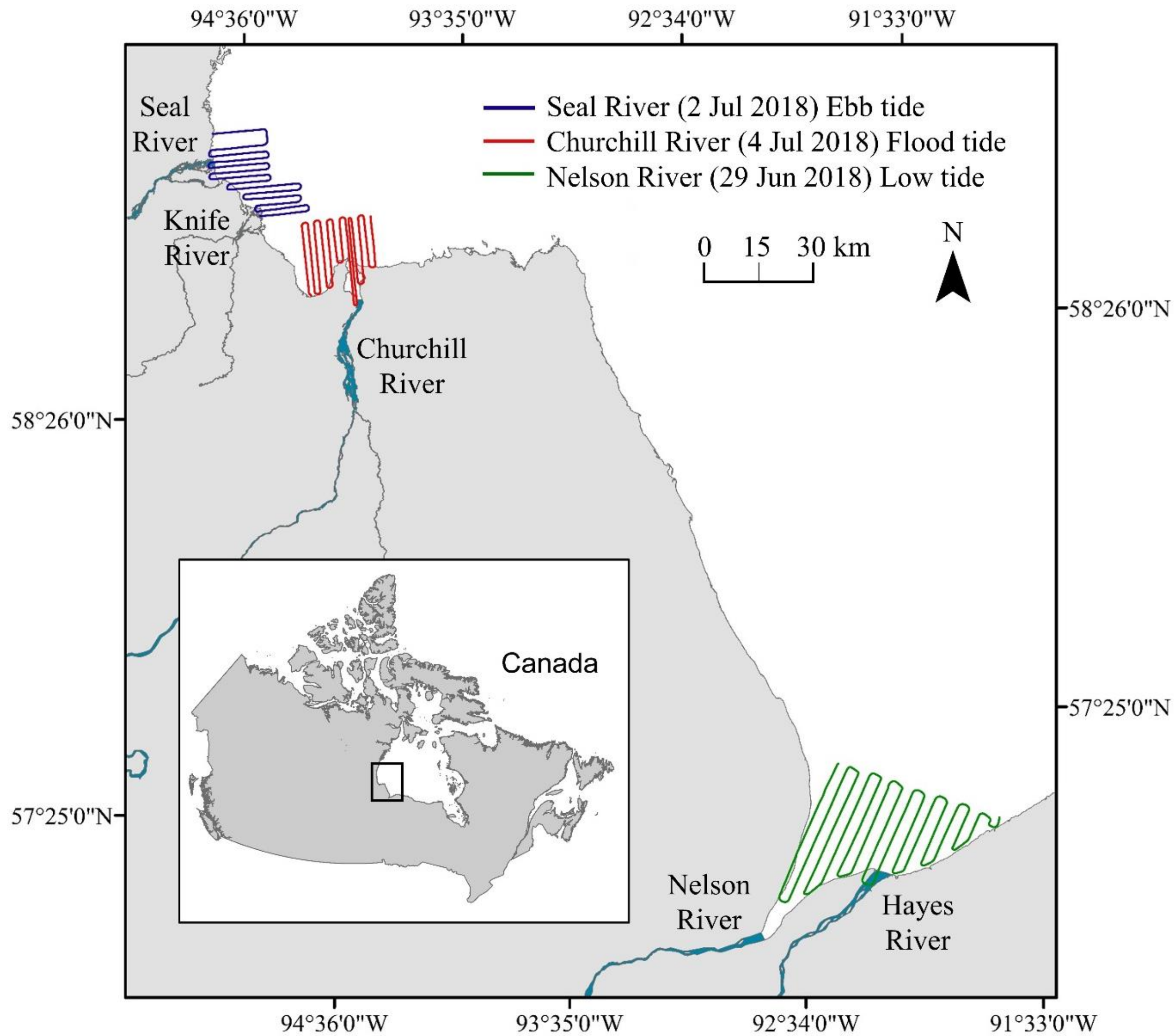


Figure 2. 1 Aerial photographic survey transect lines for the each of the locations in the Seal, Churchill, and Nelson river estuaries flown in June and July 2018.

2.4.2 Habitat variables

Habitat data was collected using remotely sensed data from MODIS and Sentinel 2 as well as through calculating the distance to environmental features. Variables collected included distances to different river mouths (m), surface colored dissolved organic matter concentration (CDOM) (m^{-1}), sea surface temperature (SST) (°C), surface chlorophyll a concentration (mg/m^3), distance to shore (m), distance to intertidal areas (m), distance to the 50% river CDOM influenced water (m), total suspended sediment concentration (TSS) (g/L), and bathymetry (m). The intertidal zone was outlined in ArcMap using low tide Sentinel 2 RGB images. In the

Churchill survey area, the distance to intertidal zone and distance to shore were combined in one additional variable as the intertidal zone did not continue across the shoreline. Distance measurements were calculated using the cost distance tool in ArcMap to create a 10 m resolution raster, where each pixel contained the distance from the pixel to the environmental feature, avoiding shoreline boundaries. As intertidal areas were removed from river plume analysis, points falling within the intertidal zone were given a distance value of 1 m for distance to the 50% river CDOM influenced water. Locations within the boundaries of the 50% river CDOM influenced water were also given a distance value of 1 m. Bathymetry was available for the Nelson River estuary at 1 m resolution from Manitoba Hydro. Remotely sensed habitat variables were collected for the Nelson, Churchill and Seal River estuaries in the days surrounding the survey dates. Raster areas with no data, with outliers, or where clouds covered a small portion of the images were removed using a mask and not considered in this analysis (Figure 2).

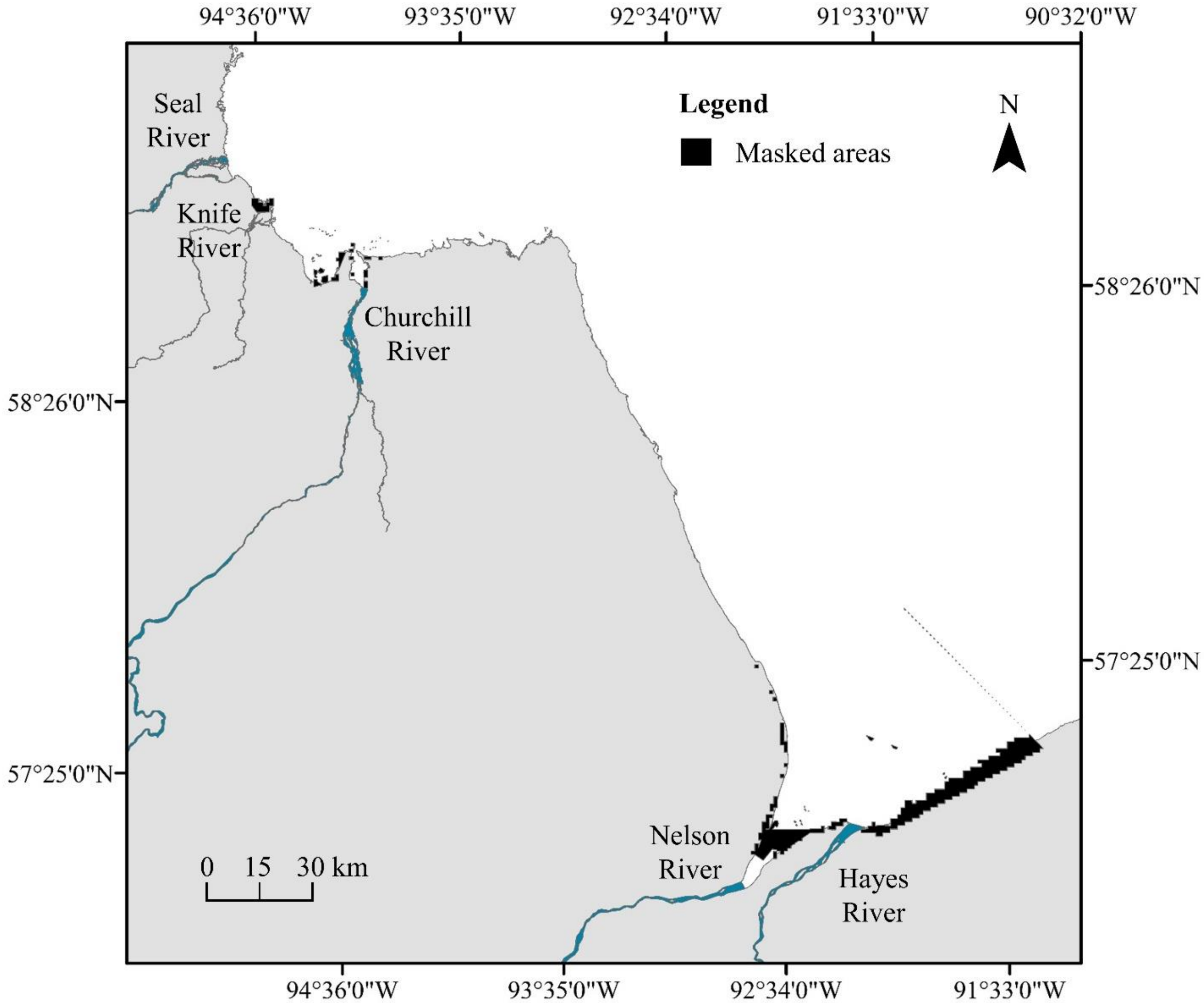


Figure 2. 2 Areas masked from analysis for all habitat areas after removing outliers and area with cloud cover from satellite imagery raster's.

2.4.2.1 Modis

Level 2 Aqua and Terra ocean color and sea surface temperature data at 1 km resolution were downloaded from NASA's Ocean Color website (https://oceancolor.gsfc.nasa.gov/). These files were re-projected for use in ArcMap using SeaDAS (SeaDAS Version 7.5.3, https://seadas.gsfc.nasa.gov/, accessed 10 Sep 2020). Several sections of missing pixels were calculated through interpolation in the geospatial wizard tool in ArcMap, by first converting the raster values to points, then sub-setting 80% of the points into a training layer and 20% in a testing layer used to confirm the prediction/interpolation (Figures 2. 3-2. 5). The most accurate interpolation was kriging using a gaussian model. Aqua and terra habitat variables were collected from the day of the survey, when possible, or the closest available day. The processes done to compile values for each survey date are listed in Table 1.

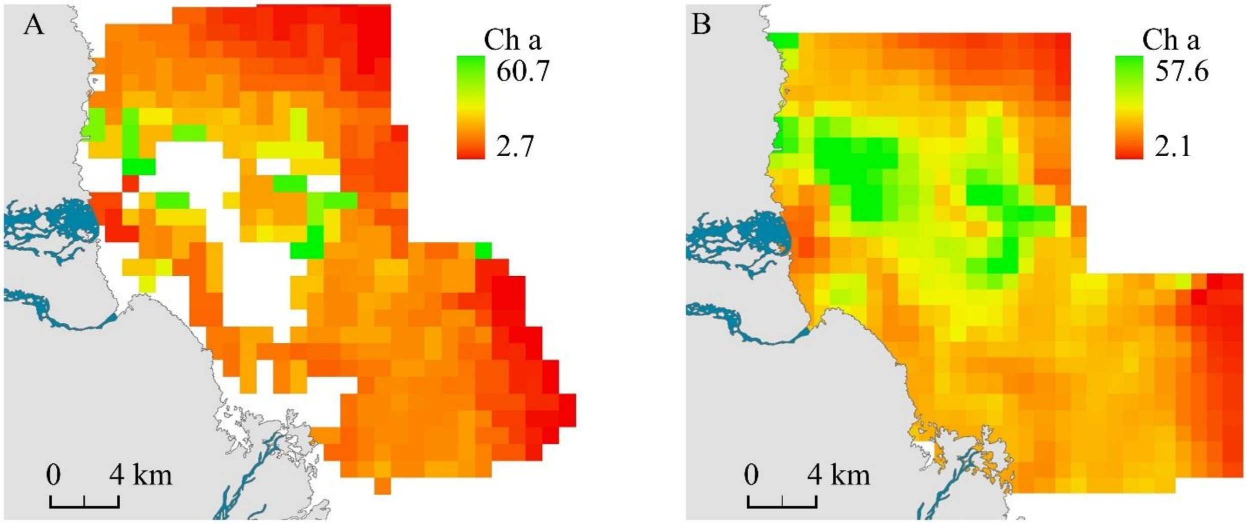


Figure 2. 3 Surface chlorophyll a values from MODIS Aqua level 2 data on 3 July 2018 for the Seal River area (A) with white areas as missing pixel values. Interpolated values and complete surface Chlorophyll a map for the Seal River area (B).

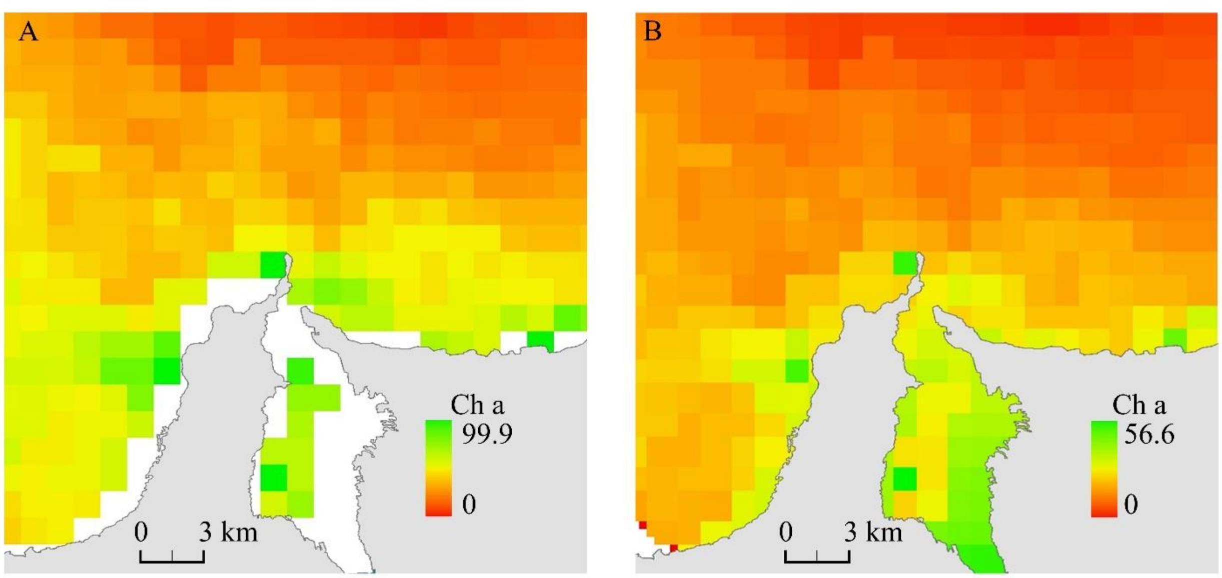


Figure 1. Surface chlorophyll a values from MODIS Terra level 2 data on 4 July 2018 for the Churchill River area (A) with white areas as missing pixel values. Interpolated values and complete surface Chlorophyll a map for the Churchill River area (B).

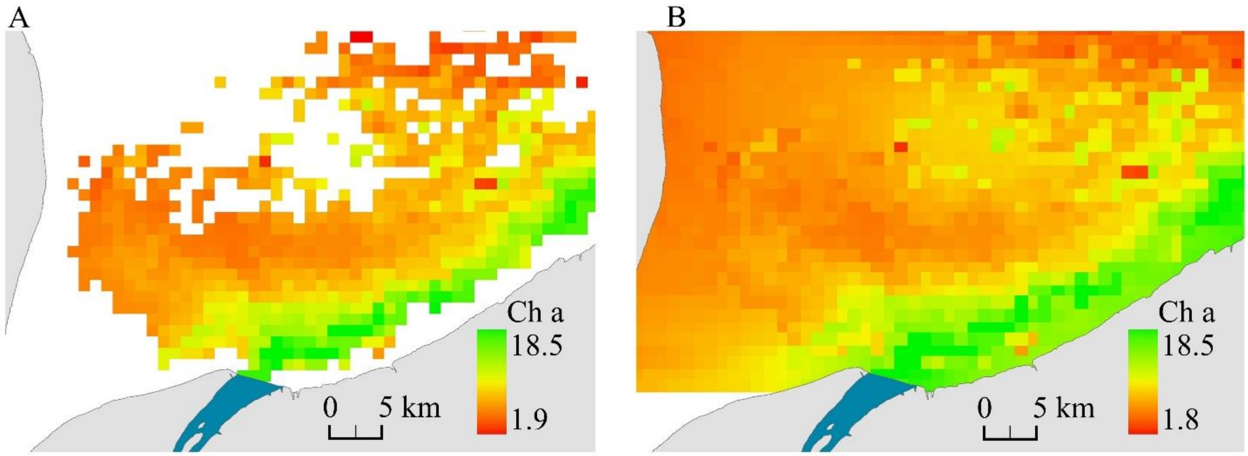


Figure 2. 4 Surface chlorophyll a values from MODIS Terra level 2 data on 30 June 2018 for the Nelson River area (A) with white areas as missing pixel values. Interpolated values and complete surface Chlorophyll a map for the Nelson River area (B).

Table 2. 1 Methods used to compile MODIS satellite imagery for each aerial survey location and date.

Date	Location	Chlorophyll a	Sea surface temperature
June 29th, 2018	Nelson	Terra June 30th values. Aqua and terra values interpolated using geostatistical analysis to get missing values. Raster calculator used to replace null cells with the interpolated values.	Terra June 30th
July 2nd, 2018	Seal	Aqua July 3rd values. Interpolated using geostatistical analysis to get missing values. Raster calculator used to replace null cells with the interpolated values.	Terra July 3rd
July 4th, 2018	Churchill	Aqua July 4th values. Interpolated using geostatistical analysis to get missing values. Raster calculator used to replace null cells with the interpolated values.	Terra July 4th

2.4.2.2 Sentinel 2

Sentinel 2 images at 10-m resolution in the month surrounding survey dates (Table 2) (https://scihub.copernicus.eu/dhus/#/home) were used to calculate concentration of total suspended sediment (TSS) and colored dissolved organic matter (CDOM). Remote sensing reflectance at 665 nm (Red- B4) was used to retrieve TSS following Nechad et al. (2010) (eq 1). Similarly, blue (490 nm, B2) and red (665 nm, B4) bands were utilized to retrieve CDOM (Campanelli et al., 2017; Doxaran et al., 2005)(Basu et al., 2022, submitted) (eq 2). These optical algorithms were calibrated using in-situ data collected from western Hudson Bay.

High sediment concentrations in the intertidal mudflats of western Hudson Bay River estuaries prevent the optical tracing of river plume boundaries using TSS (Basu et al., 2022, submitted). CDOM sourced from the rivers were used as an optical tracer of river plumes (Fichot & Benner, 2014). Spatial distribution of optically retrieved CDOM in the Churchill and Seal River estuary and their coastal waters were analyzed to demarcate the river plume boundaries (Table 3). The offshore boundaries represented as distances from river mouth corresponded to 50%, 75% and 100% dilution of the river CDOM values for the Churchill River (Figure 6) and Seal/Knife rivers (Figure 7) (Basu et al., submitted). The distance of each beluga to the 50% river CDOM influenced water was used as an environmental variable in modeling. These values were not calculated for the Nelson River as belugas were located within the estuary which is dominated by river waters, and the plume would extend beyond the high intensity area of belugas. For each area the concentration (CDOM, TSS) and distance (50% river CDOM influenced water) were calculated for each available Sentinel 2 image, then averaged (Table 2).

$$\mathrm{TSS} = 925.12(\mathrm{B4}) - 0.2088 \qquad (1)$$

$$CDOM = \left(2.2105 * \left[\left(\frac{B2}{B4}\right)^{-1.244}\right]\right) \qquad (2)$$

Environmental characteristics associated with both beluga and randomly generated locations were collected by extracting raster information to points in ArcMap. Analysis was conducted in R (R 4.1.1, https://cran.r-project.org/, accessed 12 Sep 2021). For these analyses, environmental variables were scaled using the standardize package in R then tested for multicollinearity by looking at Pearson correlation in the R stats package (Eager, 2017; Legendre & Legendre, 1998; R Core Team, 2021). Highly correlated values (> 0.9) were not included in the same models unless assessed to describe environmental variables with valuable differences.

Table 2. 2 Cloud free sentinel 2 images used to create averaged CDOM and TSS concentration raster’s by each aerial survey location.

Image	Date	Survey Location
S2A	20 June 2018	Churchill and Seal rivers
S2B	22 June 2018	Nelson River
S2A	30 June 2018	Churchill and Seal rivers
S2B	22 July 2018	Nelson River
S2B	25 July 2018	Churchill and Seal rivers
S2B	28 July 2018	Churchill and Seal rivers

Table 2. 3 River flow, and tide for the Churchill and Seal rivers for each satellite image used for river plume delineation

		River flow (m3/s)	
Date	Tide	Churchill River	Seal River
20 June 2018	High	667	1110
30 June 2018	Ebb	593	1120
25 July 2018	Low	756	784
28 July 2018	Flood	787	739

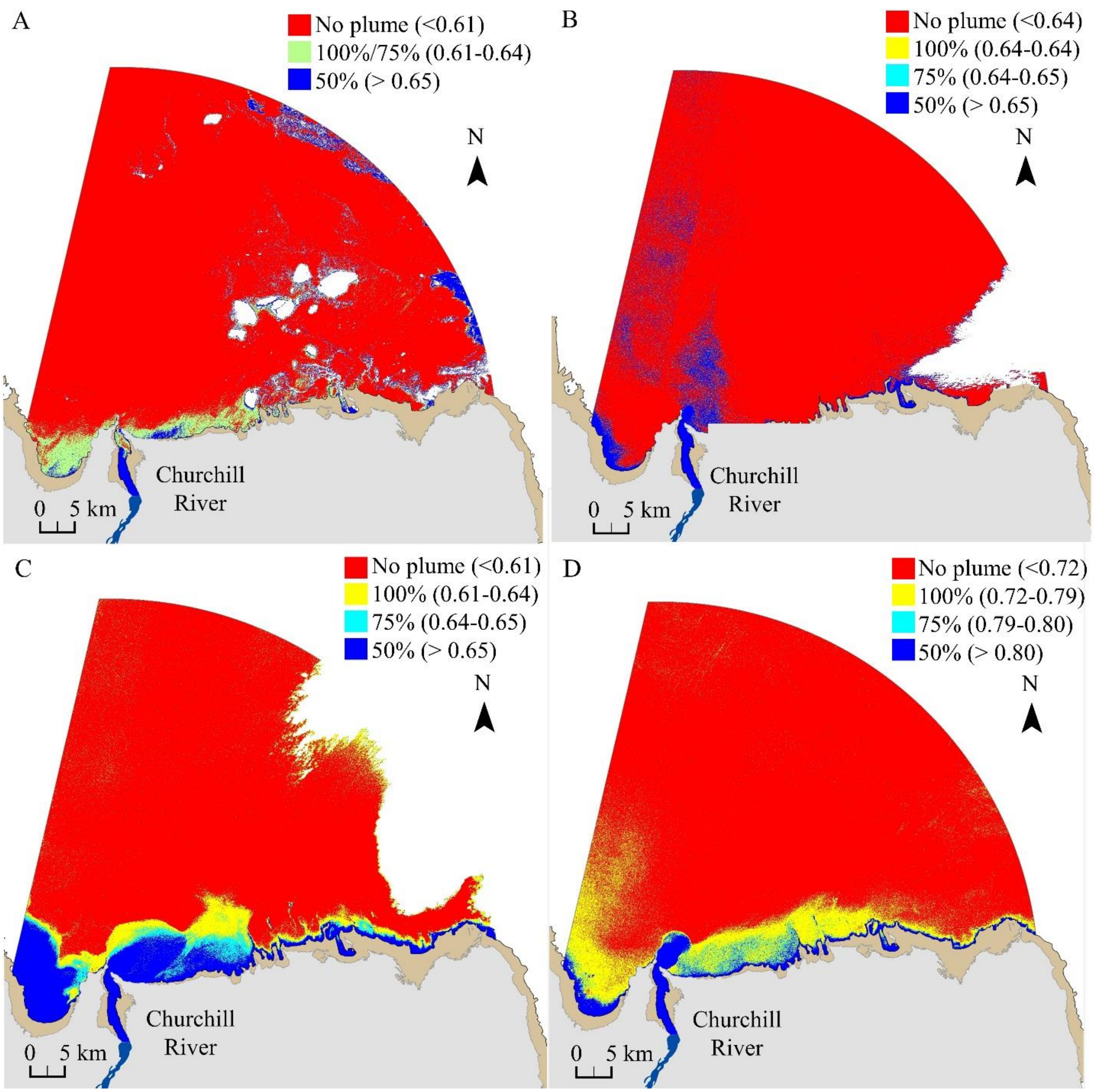


Figure 2. 5 Churchill River plume boundaries as represented by the 50% (blue), 75% (teal) and

100% (yellow) dilution of the river CDOM values. Areas in red represent areas with no plume, areas in white represent cloud or ice cover, intertidal zone is tan. CDOM (colored dissolved organic matter) concentration for each of the plume boundaries are shown for each date in parentheses. Boundaries were compiled from Sentinel 2 imagery taken on June 20, 2018 (A), June 30, 2018 (B), July 25, 2018 (C) and July 28, 2018 (D). The 75% and 100% boundaries were combined on June 20 2018 (A), which is represented in light green.

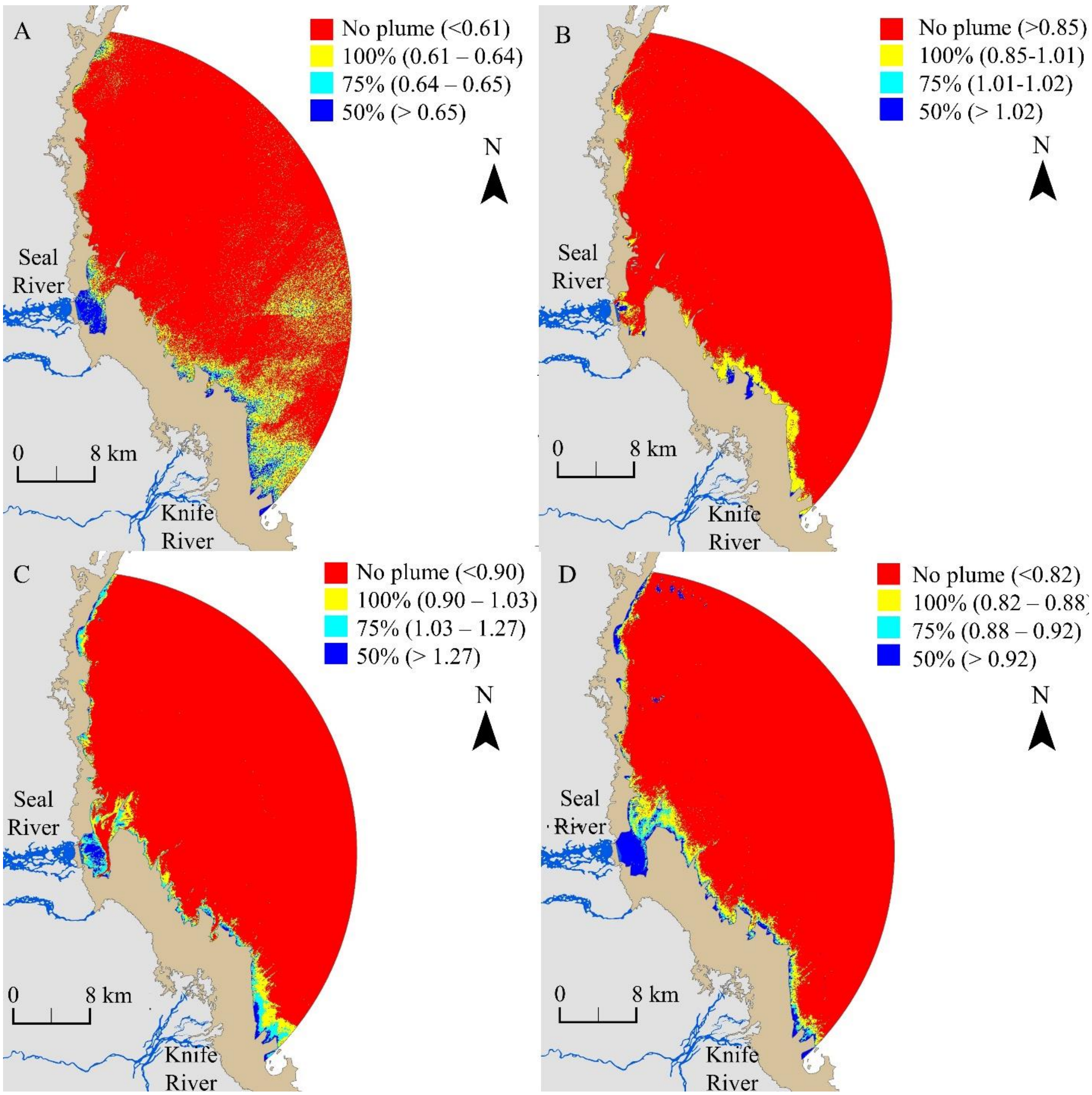


Figure 2. 6 Seal and Knife River plume boundaries as represented by the 50% (blue), 75% (teal) and 100% (yellow) dilution of the river CDOM values. Areas in red represent areas with no

plume, the intertidal zone is tan. CDOM (colored dissolved organic matter) concentration for each of the plume boundaries are shown for each date in parentheses. Boundaries were compiled from Sentinel 2 imagery taken on June 20, 2018 (A), June 30, 2018 (B), July 25, 2018 (B) and July 28, 2018 (D).

2.4.3 Analysis

2.4.3.1 MDA

Spatial scale is an important consideration in modeling habitat (Manly et al. 1993, Boyce 2006). As the WHB beluga occupy a wide range of habitat, we sought to separate surveyed areas according to the environmental characteristics that would impact beluga distribution. To determine patterns in estuary use we defined the spatial scale in advance through categorizing beluga habitat areas by the closest river (Seal, Knife, Churchill, Nelson or Hayes rivers). Additionally, the enclosed Churchill River estuary includes unique environmental characteristics from the offshore area, which could drive differential beluga habitat use. To test for river and estuary/offshore habitat area differences, we performed multiple discriminant analysis (MDA) using environmental characteristics associated with beluga locations. Multiple discriminant analysis (MDA) is a method that generates discriminant functions that maximally separate *a priori* naturally defined groups on each discriminant axis based on an independent set of predictor variables (Hair et al. 2014). Groups were defined geographically based on the closest river mouth (Seal River, Knife River, Nelson River), as well as Churchill River offshore vs Churchill River estuary locations. Discrimination was performed on the marine environmental parameters measured in those areas where belugas were present. Although MDA can be used to construct resource selection functions, in this study it was used to characterize differences in marine habitats and the importance of the environmental parameters by examining discriminant weights (Manly et al., 2002). Two MDAs were completed, the first with beluga from all river estuaries (with two habitat areas for the Churchill River) using the environmental variables of distance to shore, distance to the closest river mouth, TSS, CDOM, Chlorophyll a, SST, and distance to intertidal zone. The second was run using beluga in all habitat areas except for the Nelson River, and all variables from the first MDA as well as distance to distance to the 50%

river CDOM influenced water.

MDA was completed using the package MASS in R (Ripley et al. 2019). To meet the assumptions of a MDA, data must be normally distributed, independent variables are not multicollinear and there should be equal dispersion in variances (Hair et al. 2014). Histograms were used to check for normal distribution using ggplot2 in R, and Pearson correlation between variables were tested for all beluga locations (Wickham, 2016). A multivariate analysis of variance (MANOVA) was used to test for overall significance of all axis, and Wilks lambda was used to test for significance of subsequent discriminant axes using the stats and candisc packages in R (Friendly & Fox, 2021; Legendre & Legendre, 1998). Discriminant plots were visualized using the package ggord in R (Beck, 2022).

2.4.3.2 RSF

Resource Selection Function analyses are methods to assess the importance of habitat resources based on the probability of use (Manly, et al. 2002). There are two broad classes of approach (Boyce et al. 2002): presence/absence (used and unused) and presence/available (presence-only). As it is not possible to determine where belugas were absent from an aerial survey, a presence and available logistic resource selection function was used (eq 3). β_i gives the coefficient for each habitat variable (x_i), and w(x) gives the relative probability of use of a resource unit for k habitat variables measured at the location (Boyce et al., 2002; Manly et al., 2002).

$$w(x) = \exp\,(\beta_1 x_1 + \beta_2 x_2 + \cdots \beta_k x_k) \quad (3)$$

The package ResourceSelection was used to run RSF for each habitat area using combinations of habitat variables without including highly correlated characteristics within the same model (Table 2.4) (Lele et al., 2019). Beluga locations marked in the survey were considered present locations, and available habitat locations were generated randomly within polygons covering the area of the photographic coverage of survey tracks. In the Churchill River estuary area, available locations were generated within the whole of the estuary as this could better represent habitat use of such a small area (33 km^2). For each area 60,000 available points were generated randomly, from which a subset was used for model selection and for determining model coefficients. We chose the appropriate subset size of available points for each habitat area by considering the size of the area (km^2) and the variance in the satellite derived variables, adding more available points in locations with higher environmental variability (Table 2.5).

. Bayesian Information Criteria (BIC) is a model selection method that choses the model that best represents habitat use while maintaining as much model simplicity as possible (Boyce et al., 2002; Schwarz, 1978). Model selection was conducted in R using the stats and dplyr packages (R Core Team, 2021; Wickham et al., 2021). BIC values for each model (using different combinations of non-correlated habitat variables, table 2.4) were determined and the model with the lowest BIC was chosen (R Core Team, 2021) .Model selection was iterated 1000 times, where in each iteration resource selection functions were built for all model combinations using a subset of available points randomly selected from the 60,000 generated locations in each area. The model chosen the most across iterations was used as the final model for each habitat area.

Sensitivity analysis was conducted on the model coefficients from the final model to confirm the available sample size was high enough to appropriately reduce the variation (Northrup et al., 2013). This was done by plotting the variation in model coefficients (β_i) with the available sample size. For this, available locations from the 60,000 generated locations were randomly selected at a sample size between a number equal to the belugas in each area and 50 times as many belugas in each area. Model validation was completed on the best BIC selected model by running k-fold cross validation (k=5) with spearman’s rho (Boyce et al., 2002).

Table 2. 4 Habitat variables used for model selection by habitat area. Model combinations are represented by adding variables together (+). When variables are correlated and are not included in the same model "or" separates the variables. Ch a represents surface chlorophyll a concentration, SST represents sea surface temperature, TSS represents total suspended sediment concentration (Sentinel 2), CDOM represents concentration of colored dissolved organic matter (Sentinel 2).

Location	Environmental variables	Total Variables	Total Models
Seal River offshore	CDOM or TSS + Ch a + distance to Seal River mouth or distance to 50% river CDOM influence water + distance to intertidal zone or distance to shore + SST	8	86
Knife river offshore	CDOM or TSS + Ch a + distance to Knife River mouth or distance to 50% river CDOM influence water + distance to intertidal zone or distance to shore + SST	8	86
Churchill River offshore	CDOM or TSS + Ch a + distance to Churchill River mouth or distance to 50% river CDOM influence water + distance to intertidal zone or distance to intertidal zone with shore or distance to shore + SST	9	132
Churchill River estuary	CDOM or TSS + Ch a + distance to Churchill River mouth or distance to 50% river CDOM influence water + distance to intertidal zone or distance to intertidal zone with shore or distance to shore + SST	9	132
Nelson River offshore	Bathymetry + CDOM or TSS + Ch a + distance to Nelson River + distance to Hayes River + distance to intertidal zone or distance to shore + SST	9	278

Finally, the selected models for each area were used to create maps showing predicted optimal habitat areas. For each habitat area, a 100 m grid was created in ArcMap and the mean habitat variable for each square was extracted. After variables were scaled, the final resource selection function was used predict occupation of each 100m grid. Predicted values were rescaled between 0 and 1 using a linear stretch, where $\widehat{w}$ is the adjusted value of w(x) from equation #, w_{min} is the minumum w(x) value for the respective area and w_{max} is the maximum x(x) value from the area (eq 4) (C. J. Johnson et al., 2004).

$$\widehat{w} = \frac{w(x) - w_{min}}{w_{max} - w_{min}} \qquad (4)$$

2.5 Results

A total of 1,332 belugas in 874 groups were identified in the photographic survey (Figure 2.7, Table 2.5). Group size ranged from 1 to 10, with the largest group located in the Knife River habitat area (Table 2.5). Variation in remotely sensed habitat variables for each of the five habitat areas are shown in Table 5. Beluga habitat occupation of remotely sensed variables by each habitat area prior to scaling are shown in Figure 2.8. The density of habitat used versus all available locations for the distance to river plume in the Churchill estuary and offshore area is shown in Figure 2.9.

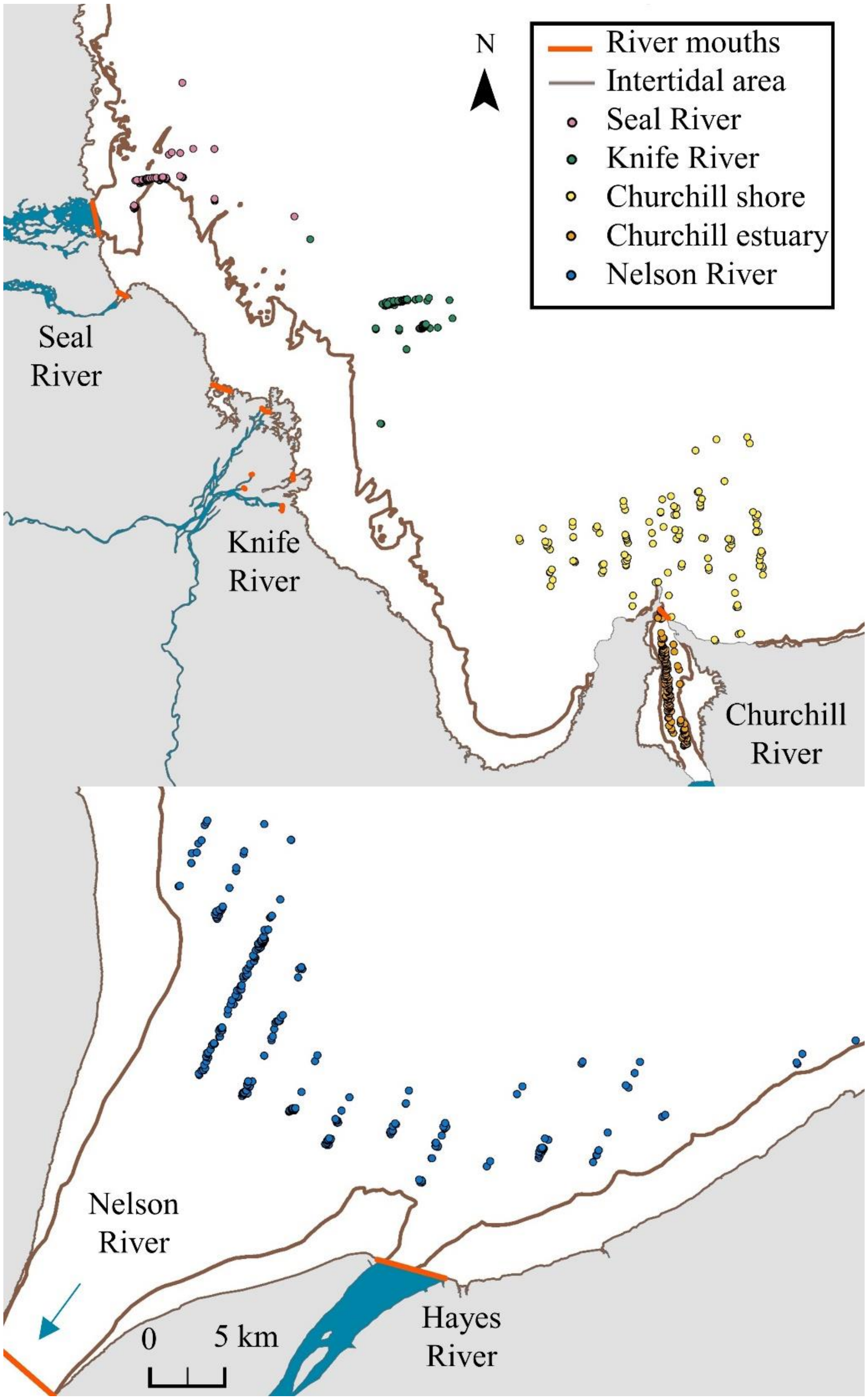


Figure 2. 7 Beluga group locations in each of the habitat areas identified from the 2018 areal survey. Each dot shows a location of an individual or a group of belugas within one body length of each other. The intertidal zone is represented by the brown line and the river mouths are represented by green lines.

Table 2. 5 The number of beluga groups, area, and variance in remotely sensed variables for each habitat area. These factors are considered to estimate available sample size for each habitat area that would appropriately represent habitat variation while building and appropriate resource selection function model

	Nelson River	Seal River	Knife River	Churchill River shore	Churchill River estuary
Beluga	318	109	166	118	163
Average group size	1.25	1.94	1.93	1.25	1.57
Range in group size	1-8	1-7	1-10	1-7	1-8
Area (km2)	108	32	36	60	33
SST	1.10	2.20	1.56	1.56	4.94
Ch a	2.55	9.65	5.75	4.04	4.60
CDOM	0.58	1.42	1.69	0.55	1.47
TSS	38.48	18.47	20.70	7.778	21.56
Available sample size	2000	1000	1000	1200	500

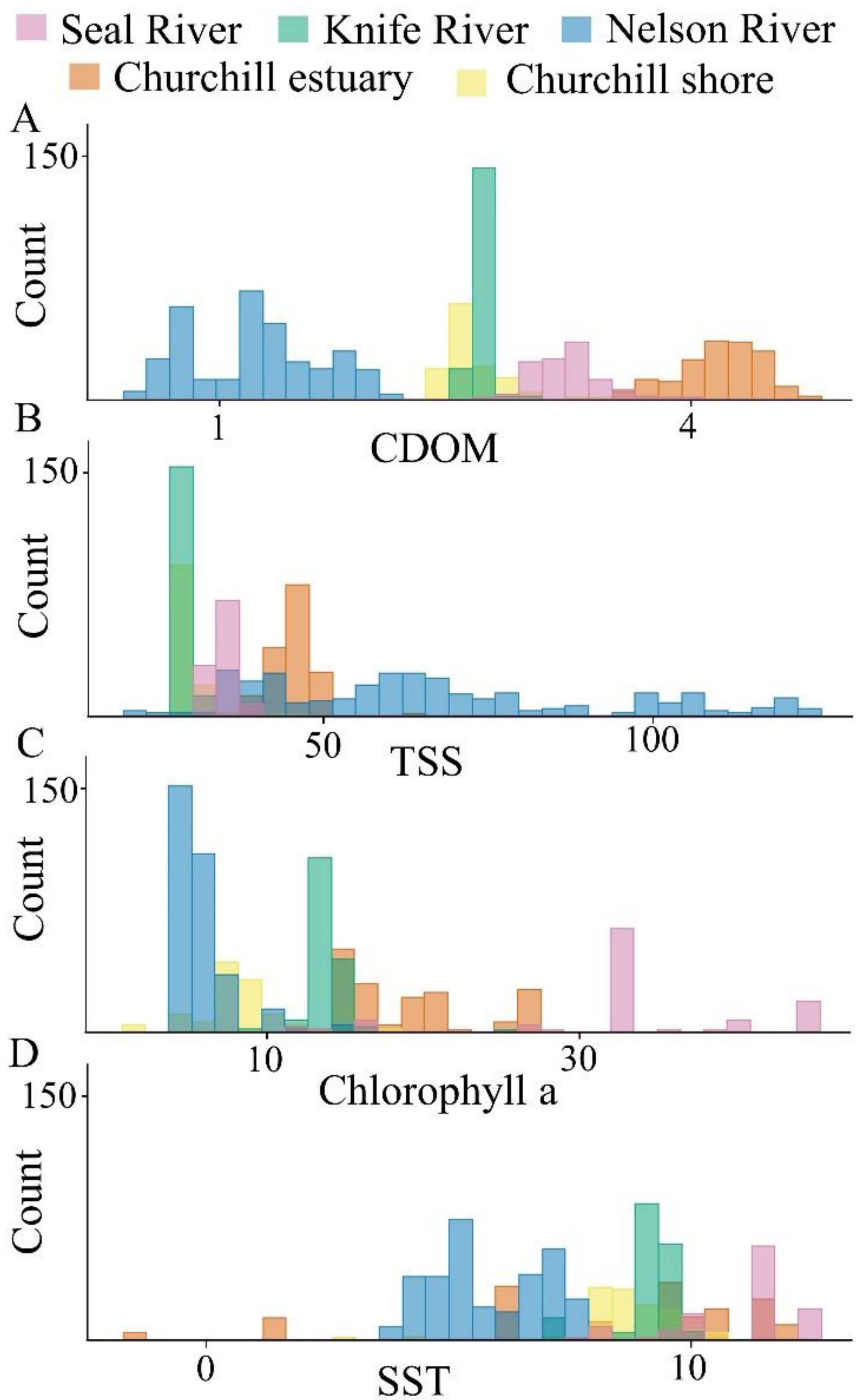


Figure 2. 8 Histograms showing the remotely sensed habitat variables (prior to scaling) associated with beluga locations by each habitat area. A) shows CDOM (colored dissolved organic matter), B) shows TSS (total suspended sediment), C) shows Chlorophyll a and D) shows SST (sea surface temperature).

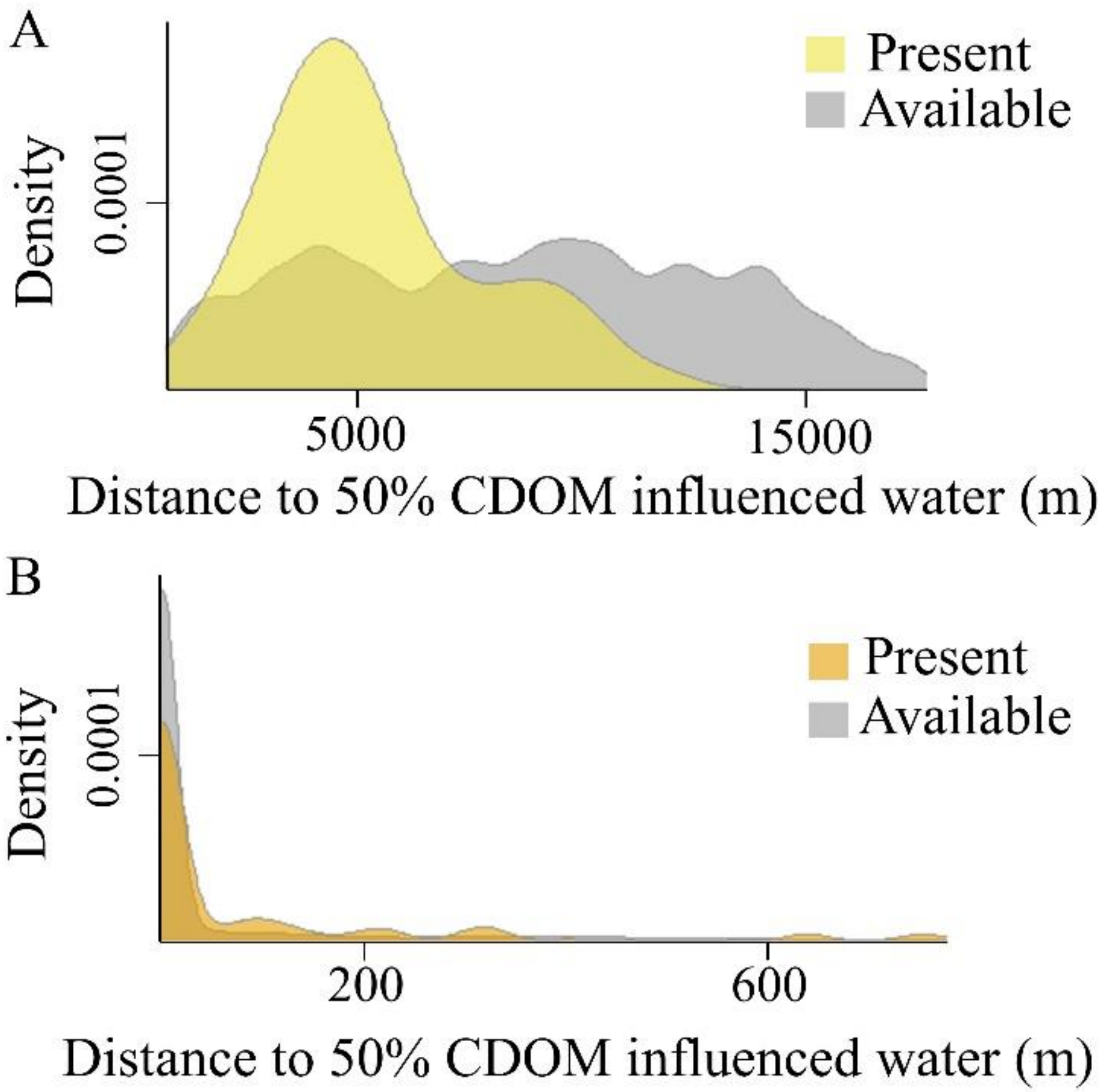


Figure 2. 9 Use of river plume habitat of beluga (yellow or orange) in the Churchill habitat areas relative to the 60,000 available locations (grey) in the Churchill River shore (A) and Churchill River estuary (B).

2.5.1 MDA

For all beluga locations the environmental variables were approximately normally distributed, and Pearson's correlation values were all below 0.86 (Table 2.6). MDA established that there are distinct habitat conditions that separate the Seal River, Knife River, Churchill River offshore, Churchill River estuary and the Nelson River For all habitat areas, the MANOVA was significant (p-vaule <0.001), and the subsequent axes as tested with Wilks Lambda were all significant (p-value <0.001). The first discriminant axis accounted for 85.9% of the total discrimination and the second accounted for 10.6% (Figure 2.10) for all habitat areas. Indicators of water quality (CDOM and TSS) contributed the most to the first discriminant axis (Table 2.7). The discrimination plots reveal significant differences between the Nelson River and Churchill estuary habitat areas, as well as the Churchill shore and Seal River habitat areas. The MDA on habitat areas excluding the Nelson River had significant MANOVA results (p-vaule <0.001), and the subsequent axes as tested with Wilks Lambda were all significant (p-value <0.001). The first discriminant axis accounted for 64.8% of the total discrimination and the second accounted for 26.7% (Figure 2.11). Distance to shore was the largest contributor to the first axis, followed by distance to intertidal zone and CDOM (Table 2.7). The discrimination plots reveal significant separation of habitat characteristics between the Knife River and Churchill estuary habitat areas, as well as the Churchill shore and Seal River habitat areas. MDA results support the separation of habitat areas for habitat modeling of beluga selection at an appropriate scale.

Table 2. 6 Pearson's correlation values for each environmental feature included when running an MDA on all locations.

	SST	Ch a	TSS	Distance to shore	Distance to river mouth	Distance to intertidal zone	CDOM
SST	1.00						
Ch a	0.52	1.00					
TSS	-0.44	-0.32	1.00				
Distance to shore	-0.36	-0.52	0.14	1.00			
Distance to river mouth	-0.69	-0.57	0.19	0.69	1.00		
Distance to intertidal zone	-0.36	-0.71	0.10	0.85	0.53	1.00	
CDOM	0.52	0.67	-0.29	-0.76	-0.79	-0.66	1.00

Table 2. 7 The discriminant scores for each variable from multiple discriminant analysis completed on all habitat areas, and all habitat areas without the Nelson River. Chlorophyll a represents Aqua or Tera (MODIS) surface chlorophyll a concentration, SST represents Tera (MODIS) sea surface temperature, TSS represents total suspended sediment concentration (Sentinel 2), CDOM represents concentration of colored dissolved organic matter (Sentinel 2).

	All habitat areas		Seal, Knife, Churchill offshore and Churchill estuary	
Environmental Variables	DA1	DA2	DA1	DA2
SST	-0.62	-0.93	-0.69	0.42
Ch a	0.18	-0.73	-0.11	0.40
TSS	2.66	-0.11	-0.49	0.35
Distance to shore	0.76	-6.38	-4.89	4.19
Distance to river mouth	-0.42	-0.36	-2.07	-0.89
Distance to intertidal zone	-0.60	4.21	3.69	-2.76
CDOM	-8.16	-1.38	3.13	2.59
Distance to 50% river CDOM influenced water			1.54	0.00

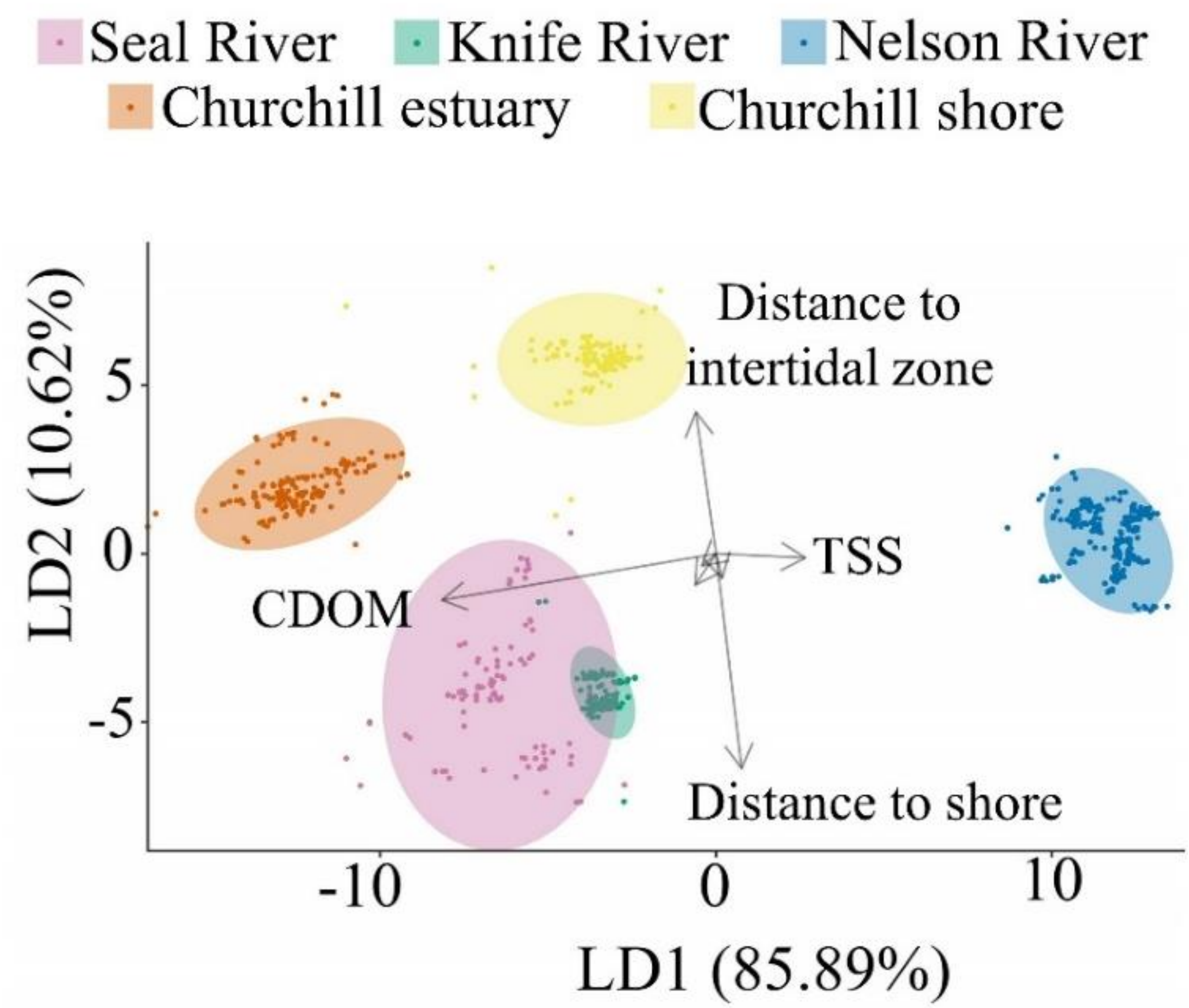


Figure 2. 10 Multiple discriminant analysis plot for the Churchill shore (orange), Churchill estuary (yellow), Seal River (purple), Knife River (pink) and Nelson River (blue) habitat areas. The variables examined are distance to shore, distance to river mouth, distance to intertidal zone, and surface concentration of colored dissolved matter, total suspended sediment and chlorophyll a. Variables with large discriminant scores on the first and second axis are displayed.

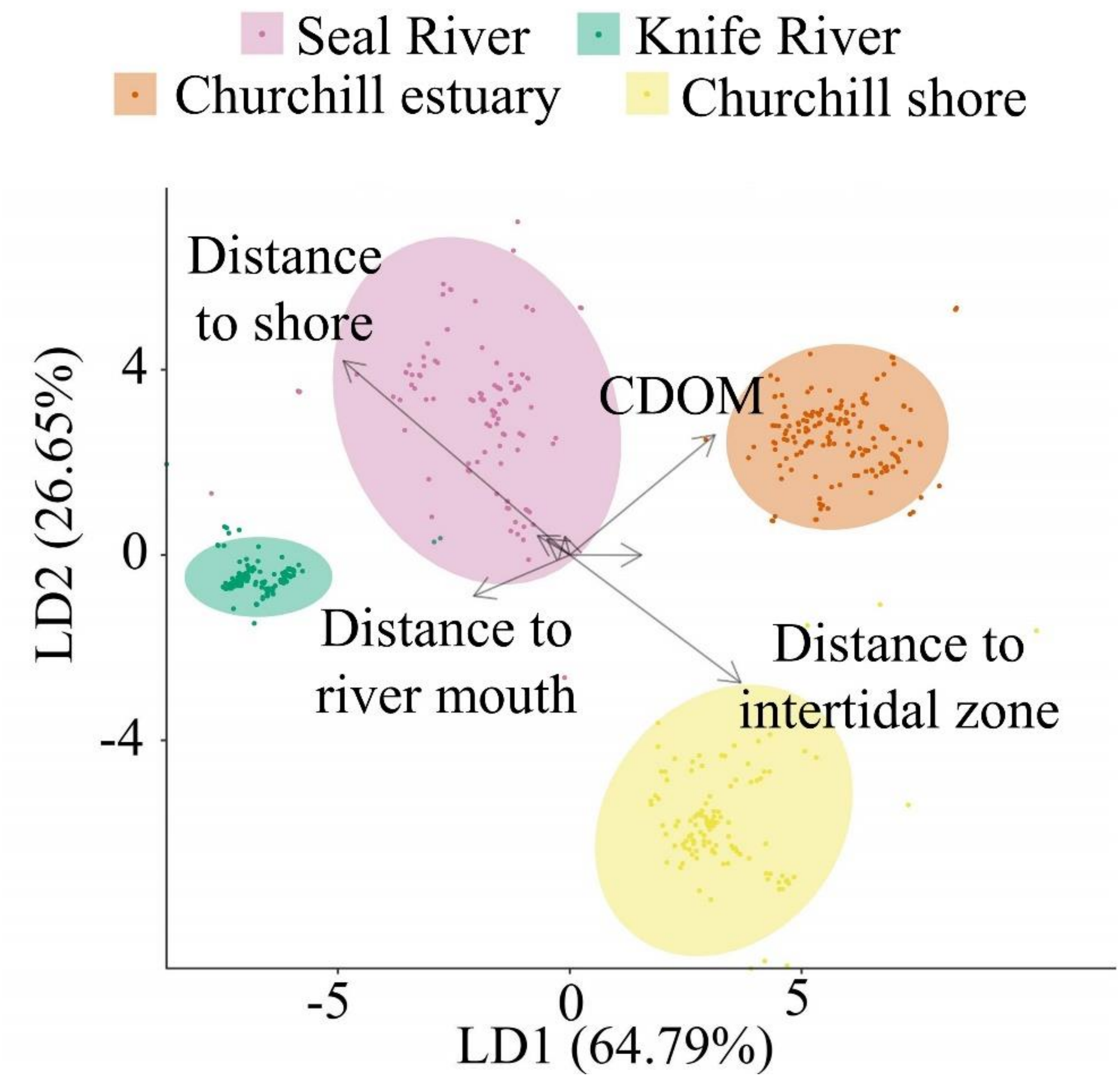


Figure 2. 11 Multiple discriminant analysis plot for the Churchill shore (yellow), Churchill estuary (orange), Seal River (pink) and Knife River (green) habitat areas. The variables examined are distance to shore, distance to river mouth, distance to intertidal zone, distance to 50% river CDOM influenced water, and surface concentration of colored dissolved matter, total suspended sediment, and chlorophyll a. Variables with large discriminant scores on the first and second axis are displayed.

2.5.2 RSF

Resource selection functions were created for the Seal River, Knife River, Churchill River offshore, Churchill River estuary, and Nelson River. High correlation (Pearson correlation > 0.90) in environmental variables for each area resulted in CDOM not being included in models with TSS, distance to river mouth not being included in models with distance to 50% river CDOM influenced water, and distance to shore not included in models with distance to intertidal areas (Tables 2.8 – 2.12). The available sample size for each area was selected based on area (km^2) and variance, with sensitivity analysis used to confirm that the sample size appropriately reduced the variance in model coefficients (Figures 2.12 – 2.16). The best model selected for each area according to BIC in the majority of the 1000 iterations is shown in Table 2.13 with model coefficients, and spearman's rho from cross validation for each model. The proportion of top models chosen with available sample size iterations out of 60,0000 random locations are shown in Tables 2.14 – 2.18.

Maps were created to show the Seal, Churchill estuary and Knife River predictions from the generated RSF, as these had the best k-fold cross validation values. After rescaling the predicted values, 5 classes were created in ArcMap using natural breaks to differentiate between low probability of use (orange) and high probability of use (blue) (Figure 2.17).

Table 2. 8 Pearson's correlation value for the Knife River estuary for all environmental variables included when running a resource selection function. Highly correlated variables are marked in bold. Distance to shore and distance to river mouth showed high correlation because these described different factors, and did not show correlation in other regions, both were kept together in models.

	SST	Ch a	TSS	Distance to shore	Distance to river mouth	Distance to intertidal zone	CDOM	Distance to 50% CDOM influenced water
SST	1.00							
Ch a	-0.22	1.00						
TSS	0.30	-0.13	1.00					
Distance to shore	-0.39	-0.04	-0.79	1.00				
Distance to river mouth	-0.42	0.01	-0.74	**0.98**	1.00			
Distance to intertidal zone	-0.19	-0.27	-0.60	**0.91**	0.89	1.00		
CDOM	0.33	-0.14	**0.97**	-0.83	-0.79	-0.64	1.00	
Distance to 50% CDOM influenced water	-0.29	-0.11	-0.62	0.94	0.94	**0.98**	-0.66	1.00

Table 2. 9 Pearson's correlation value for the Seal River estuary for all environmental variables included when running a resource selection function. Highly correlated variables are marked in bold. Distance to shore and distance to river mouth, as well as distance to intertidal zone and distance to 50% CDOM influence water showed high correlation because these described different factors, and did not show correlation in other regions, both were kept together in models.

	SST	Ch a	TSS	Distance to shore	Distance to river mouth	Distance to intertidal zone	CDOM	Distance to 50% CDOM influenced water
SST	1.00							
Ch a	-0.01	1.00						
TSS	0.37	-0.14	1.00					
Distance to shore	-0.80	0.04	-0.64	1.00				
Distance to river mouth	-0.83	-0.07	-0.58	**0.94**	1.00			
Distance to intertidal zone	-0.65	-0.27	-0.50	0.85	0.88	1.00		
CDOM	0.42	-0.14	**0.98**	-0.69	-0.65	-0.56	1.00	
Distance to 50% CDOM influenced water	-0.72	-0.14	-0.63	0.88	**0.91**	**0.93**	-0.69	1.00

Table 2. 10 Pearson's correlation value for the Churchill River shore for all environmental variables included when running a resource selection function. Highly correlated variables are marked in bold.

	SST	Ch a	TSS	Distance to shore	Distance to river mouth	Distance to intertidal zone	Distance to intertidal zone and shore	CDOM	Distance to 50% CDOM influenced water
SST	1.00								
Ch a	0.29	1.00							
TSS	-0.13	0.49	1.00						
Distance to shore	-0.06	-0.74	-0.44	1.00					
Distance to river mouth	-0.08	-0.10	0.07	0.55	1.00				
Distance to intertidal zone	-0.18	-0.84	-0.50	**0.90**	0.29	1.00			
Distance to intertidal zone and shore	-0.19	-0.85	-0.49	**0.93**	0.33	**0.99**	1.00		
CDOM	-0.11	0.51	**0.94**	-0.46	0.05	-0.52	-0.50	1.00	
Distance to 50% CDOM influenced water	0.08	0.03	0.10	0.47	**0.95**	0.15	0.19	0.08	1.00

Table 2. 11 Pearson's correlation value for the Churchill River estuary for all environmental variables included when running a resource selection function. Highly correlated variables are marked in bold. There was low correlation between distance to intertide and distance to shore, as well as distance to river mouth and distance to 50% CDOM influence water, however these variables were not included in the same model as they described similar environmental factors.

	SST	Ch a	TSS	Distance to shore	Distance to river mouth	Distance to intertidal zone	Distance to shore	CDOM	Distance to 50% CDOM influenced water
SST	1.00								
Ch a	-0.63	1.00							
TSS	0.15	0.07	1.00						
Distance to shore	-0.04	-0.26	-0.49	1.00					
Distance to river mouth	-0.75	0.53	0.14	0.02	1.00				
Distance to intertidal zone	-0.07	-0.03	-0.52	0.31	-0.20	1.00			
Distance to shore	-0.09	-0.08	-0.54	0.48	-0.15	0.88	1.00		
CDOM	0.07	0.12	**0.91**	-0.49	0.25	-0.59	-0.61	1.00	
Distance to 50% CDOM influenced water	0.35	-0.27	-0.15	-0.22	-0.66	0.34	0.17	-0.26	1.00

Table 2. 12 Pearson's correlation value for the Nelson River for all environmental variables included when running a resource selection function. Highly correlated variables are marked in bold.

	SST	Ch a	TSS	Distance to shore	Distance to Nelson River mouth	Distance to Hayes River mouth	Bathymetry	Distance to intertidal zone	CDOM
SST	1.00								
Ch a	0.39	1.00							
TSS	0.52	0.16	1.00						
Distance to shore	-0.37	-0.31	-0.69	1.00					
Distance to Nelson River mouth	-0.25	0.30	-0.66	0.37	1.00				
Distance to Hayes River mouth	-0.73	-0.34	-0.52	0.29	0.47	1.00			
Bathymetry	0.38	0.30	0.65	-0.89	-0.36	-0.37	1.00		
Distance to intertidal zone	-0.29	-0.30	-0.61	0.98	0.33	0.29	-0.89	1.00	
CDOM	0.57	0.25	**0.98**	-0.72	-0.62	-0.55	0.69	-0.64	1.00

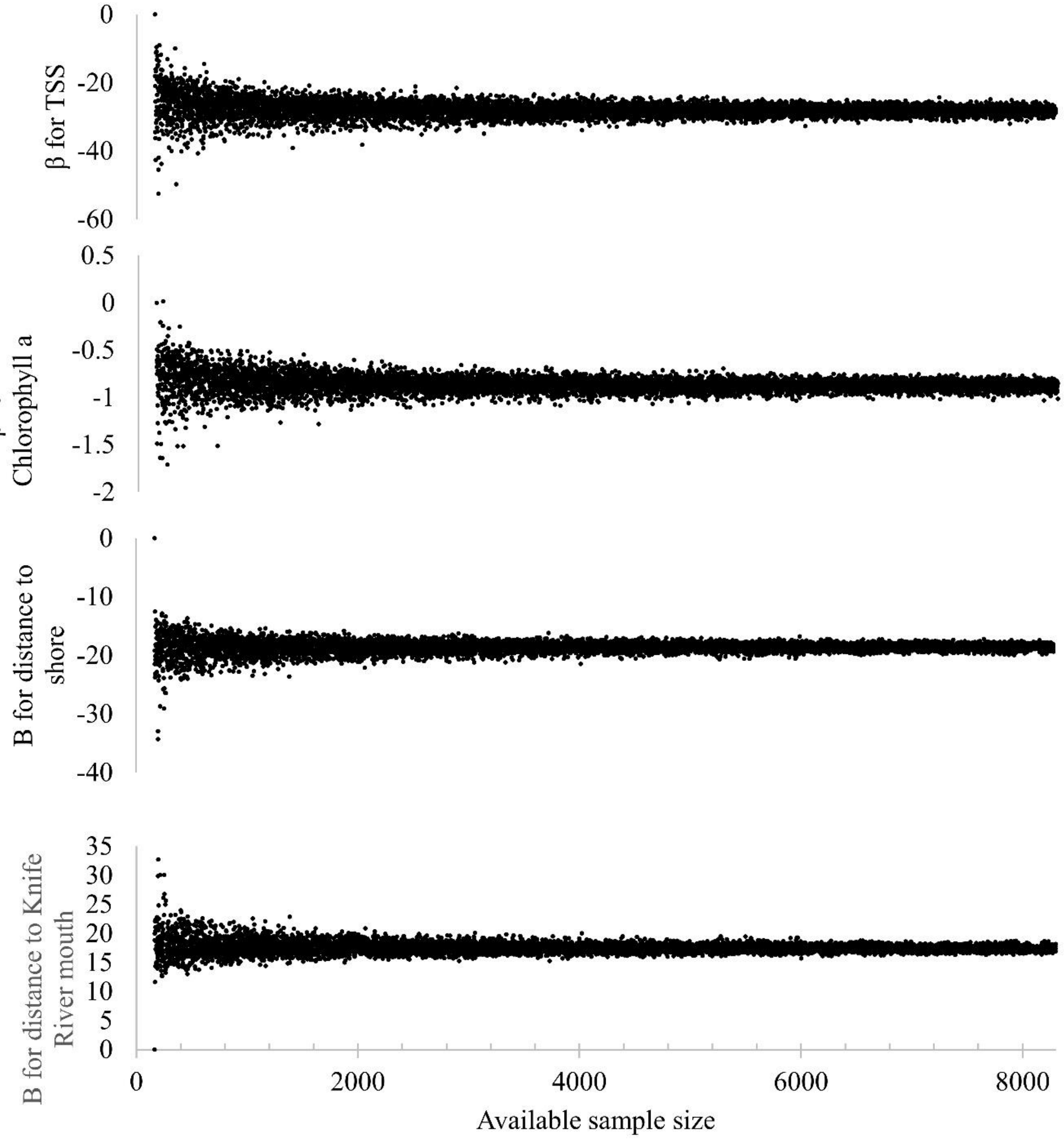


Figure 2. 12 Model coefficients for the Knife River with sample points selected from 60,000 available and a sample size up to 8,300.

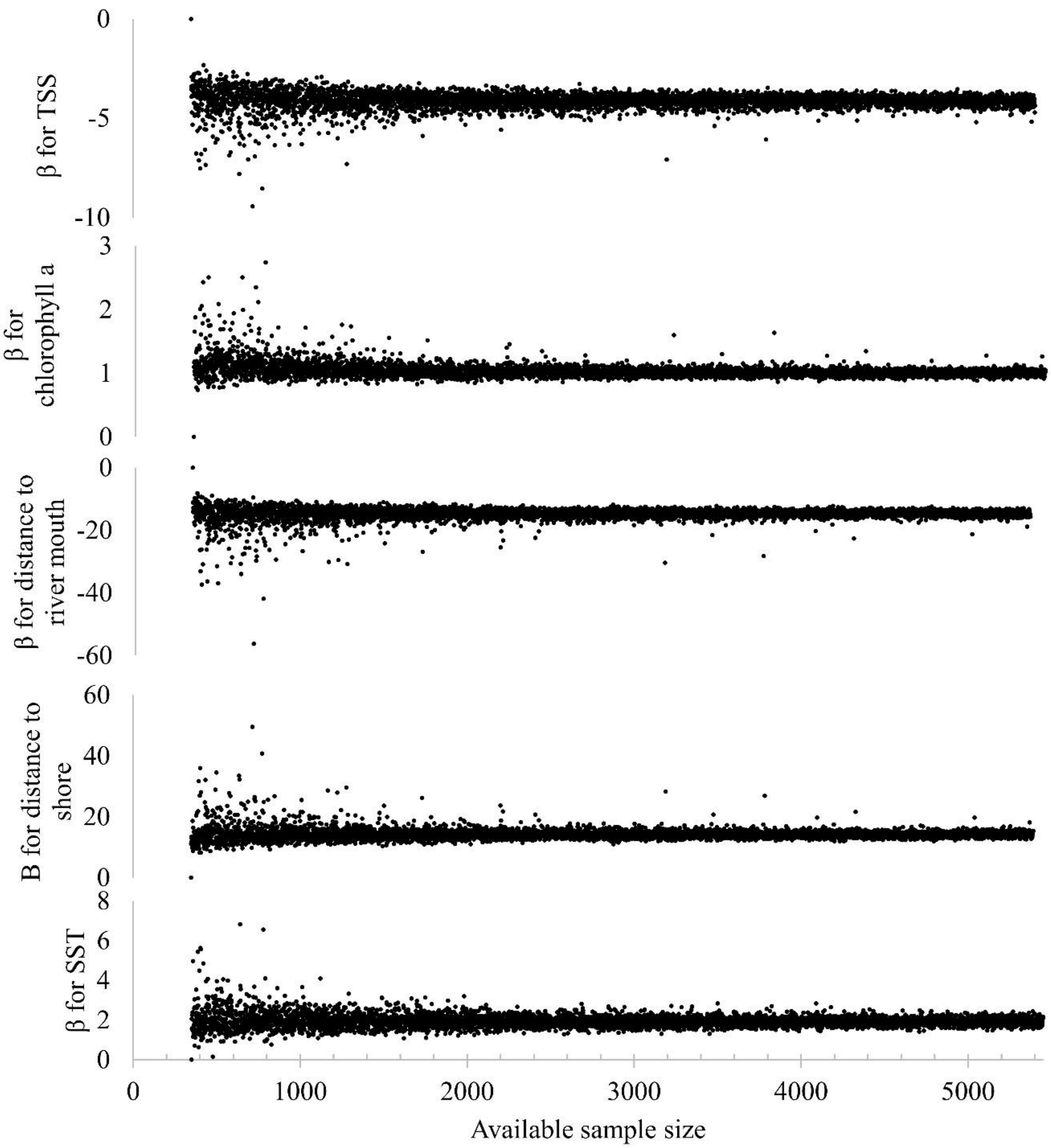


Figure 2. 13 Model coefficients for the Seal River with sample points selected from 60,000 available and a sample size up to 5,450.

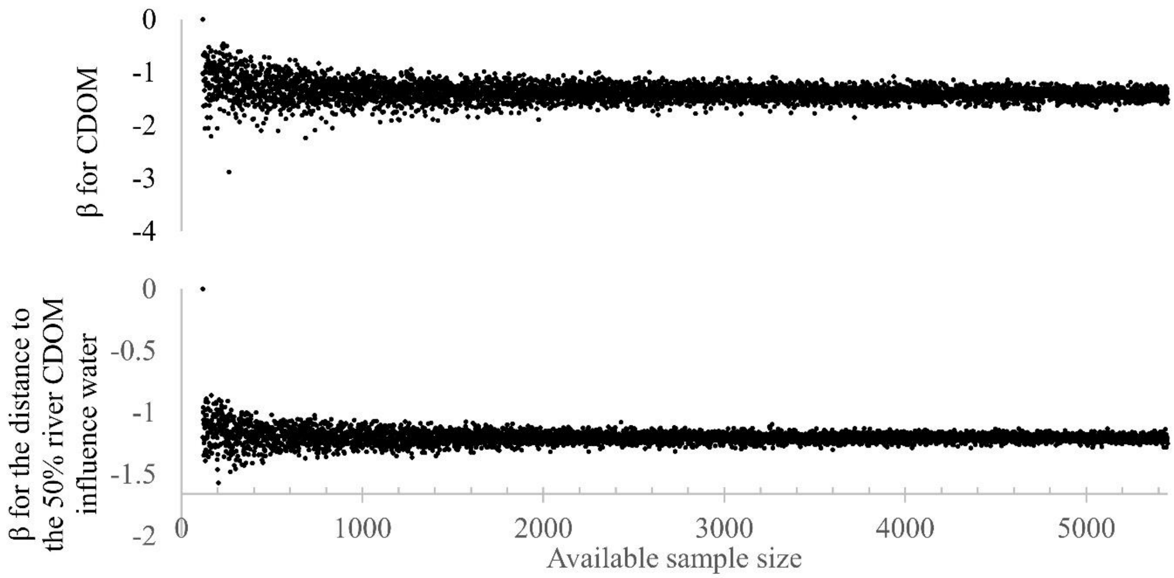


Figure 2. 14 Model coefficients for the Churchill River shore with sample points selected from 60,000 available and a sample size up to 83,000.

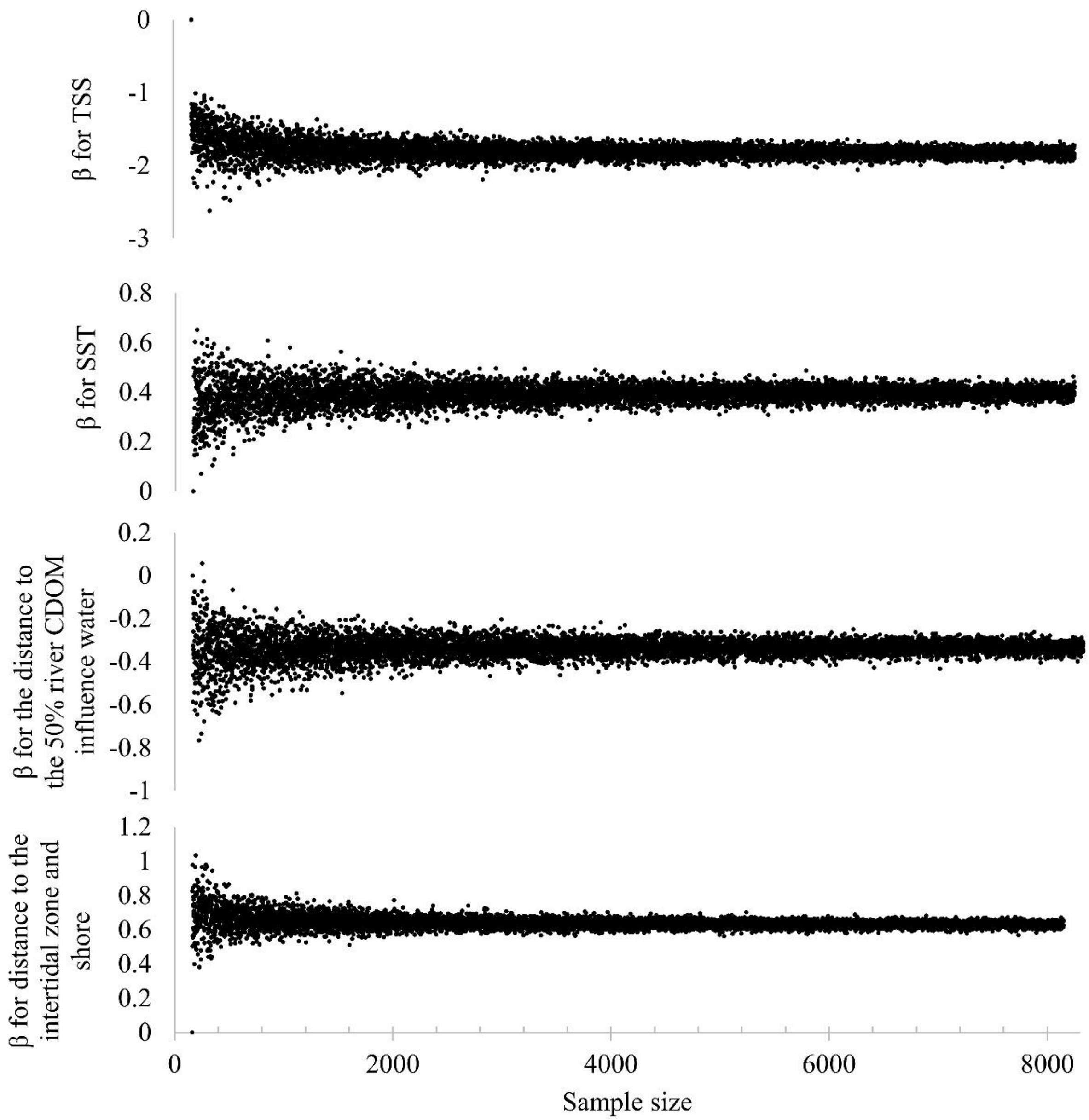


Figure 2. 15 Model coefficients for the Churchill River estuary with sample points selected from 60,000 available and a sample size up to 8,150.

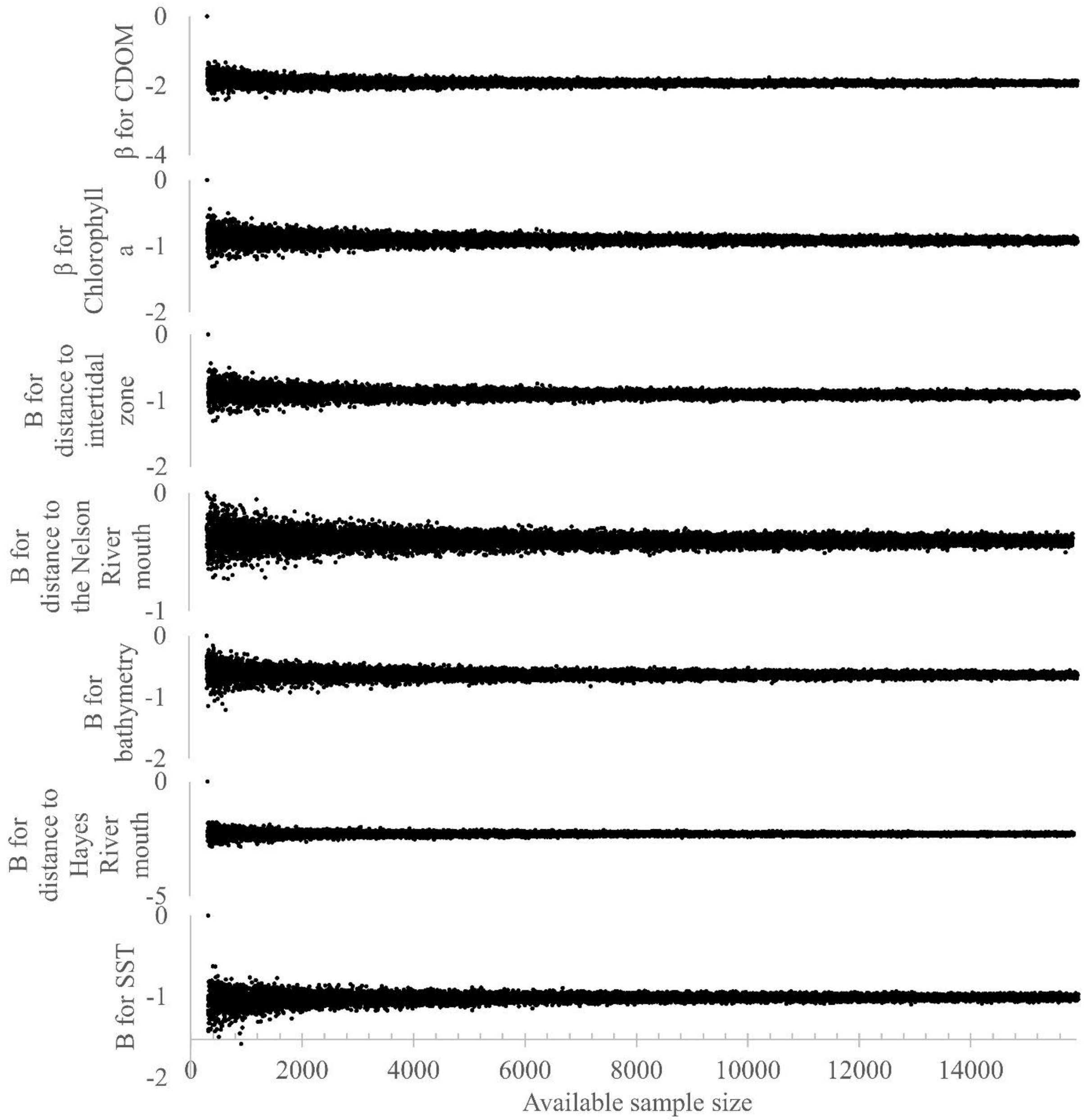


Figure 2. 16 Model coefficients for the Nelson River with sample points selected from 60,000 available and a sample size up to 15,900.

Table 2. 13 The best BIC selected model for each habitat area using 1000 iterations of BIC, the proportion this model was selected out of the 1000 locations, and the Spearman's Rho from cross validation for the model. Ch a represents surface chlorophyll a concentration, SST represents sea surface temperature, TSS represents total suspended sediment concentration (Sentinel 2), CDOM represents concentration of colored dissolved organic matter (Sentinel 2).

Location	Proportion	Best BIC selected RSF model	Spearman's Rho
Nelson River	73.2	w(x) = exp[-0.5(bathymetry) -1.9(CDOM) - 0.9(Ch a) - 0.5(distance to the Nelson river mouth) - 2.1(distance to the Hayes river mouth) -1.6(distance to the intertidal zone) - 0.9(SST)]	0.39
Churchill shore	37.6	w(x) = exp[-1.2 (CDOM) - 1.1(distance to 50% river CDOM influenced water)]	0.26
Churchill estuary	68.7	w(x) = exp[-1.8(TSS) -0.4(distance to 50% river CDOM influenced water) + 0.7(distance to intertidal zone with shore or distance to shore) + 0.5(SST)]	0.5
Knife River	49.4	w(x) = exp[-31.8(TSS) - 0.8(Ch a) + 20.8(distance to knife river mouth) - 22.0(distance to shore)]	0.51
Seal River	89.7	w(x) = exp[-3.8(TSS) + 1.1(Ch a) - 16.0(distance to river mouth) + 15.6(distance to shore) + 2.3(SST)]	0.46

Table 2. 14 Proportion of RSF models chosen during 1000 iterations of BIC model selection randomly choosing 1000 available points from the 60,000 generated in the Knife River area.

Model	Proportion (%)
TSS + Ch a + distance to river mouth + distance to shore	49.4
CDOM + Ch a + distance to river mouth + distance to shore	41.9
TSS + Ch a + SST + distance to river mouth + distance to shore	5.4
CDOM + Ch a + SST + distance to river mouth + distance to shore	3.3

Table 2. 15 Proportion of RSF models chosen during 1000 iterations of BIC model selection randomly choosing 1000 available points from the 60,000 generated in the Seal River area.

Model	Proportion (%)
TSS + Ch a + SST + distance to river mouth + distance to shore	89.7
CDOM + Ch a + SST + distance to river mouth + distance to shore	10.2
CDOM + Ch a + distance to river mouth + distance to shore	0.1

Table 2. 16 Proportion of RSF models chosen during 1000 iterations of BIC model selection randomly choosing 1000 available points from the 60,000 generated in the Churchill River shore.

Model	Proportion (%)
distance to 50% river CDOM influenced water + CDOM	37.6
SST + distance to the intertidal zone + distance to 50% river CDOM influenced water + CDOM	25.8
distance to 50% river CDOM influenced water + distance to the intertidal zone + CDOM	19.7
SST + distance to intertidal zone with shore or distance to shore + distance to 50% river CDOM influenced water + CDOM	10.2
distance to 50% river CDOM influenced water + distance to intertidal zone with shore or distance to shore + CDOM	2.3
Ch a + SST + distance to 50% river CDOM influenced water + distance to intertidal zone with shore or distance to shore + CDOM	2
Ch a + distance to 50% river CDOM influenced water + distance to the intertidal zone + CDOM	1.3
Ch a + SST + distance to 50% river CDOM influenced water + distance to the intertidal zone + CDOM	0.7
Ch a + distance to 50% river CDOM influenced water + distance to intertidal zone with shore or distance to shore + CDOM	0.4

Table 2. 17 Proportion of RSF models chosen during 1000 iterations of BIC model selection randomly choosing 500 available points from the 60,000 generated in the Churchill River estuary.

Model	Proportion (%)
SST + distance to intertidal zone with shore or distance to shore + distance to 50% river CDOM influenced water + TSS	68.7
Ch a + distance to intertidal zone with shore or distance to shore + TSS	13.2
Ch a + distance to 50% river CDOM influenced water + distance to intertidal zone with shore or distance to shore + CDOM	7.4
TSS + distance to intertidal zone with shore or distance to shore	4
SST + distance to intertidal zone with shore or distance to shore + distance to 50% river CDOM influenced water + CDOM	3
SST + distance to intertidal zone with shore or distance to shore + TSS	1.6
Ch a + SST + distance to 50% river CDOM influenced water + distance to intertidal zone with shore or distance to shore + TSS	0.5
distance to 50% river CDOM influenced water + distance to intertidal zone with shore or distance to shore + TSS	0.5
CDOM + distance to shore	0.4
distance to 50% river CDOM influenced water + distance to intertidal zone with shore or distance to shore + CDOM	0.3
SST + distance to intertidal zone with shore or distance to shore + distance to river mouth + TSS	0.2
Distance to river mouth + distance to shore + CDOM	0.1
CDOM + distance to intertidal zone with shore or distance to shore	0.1

Table 2. 18 Proportion of RSF models chosen during 1000 iterations of BIC model selection randomly choosing 2000 available points from the 60,000 generated in the Nelson River area.

Model	Proportion (%)
SST + Ch a +CDOM + distance to Nelson River mouth+ distance to Hayes river mouth + distance to the intertidal zone + bathymetry	73.2
SST + Ch a +CDOM + distance to the Hayes River mouth + distance to the intertidal zone + bathymetry	26.7
SST + Ch a +TSS + distance to the Hayes River mouth + distance to intertidal zone + bathymetry	0.1

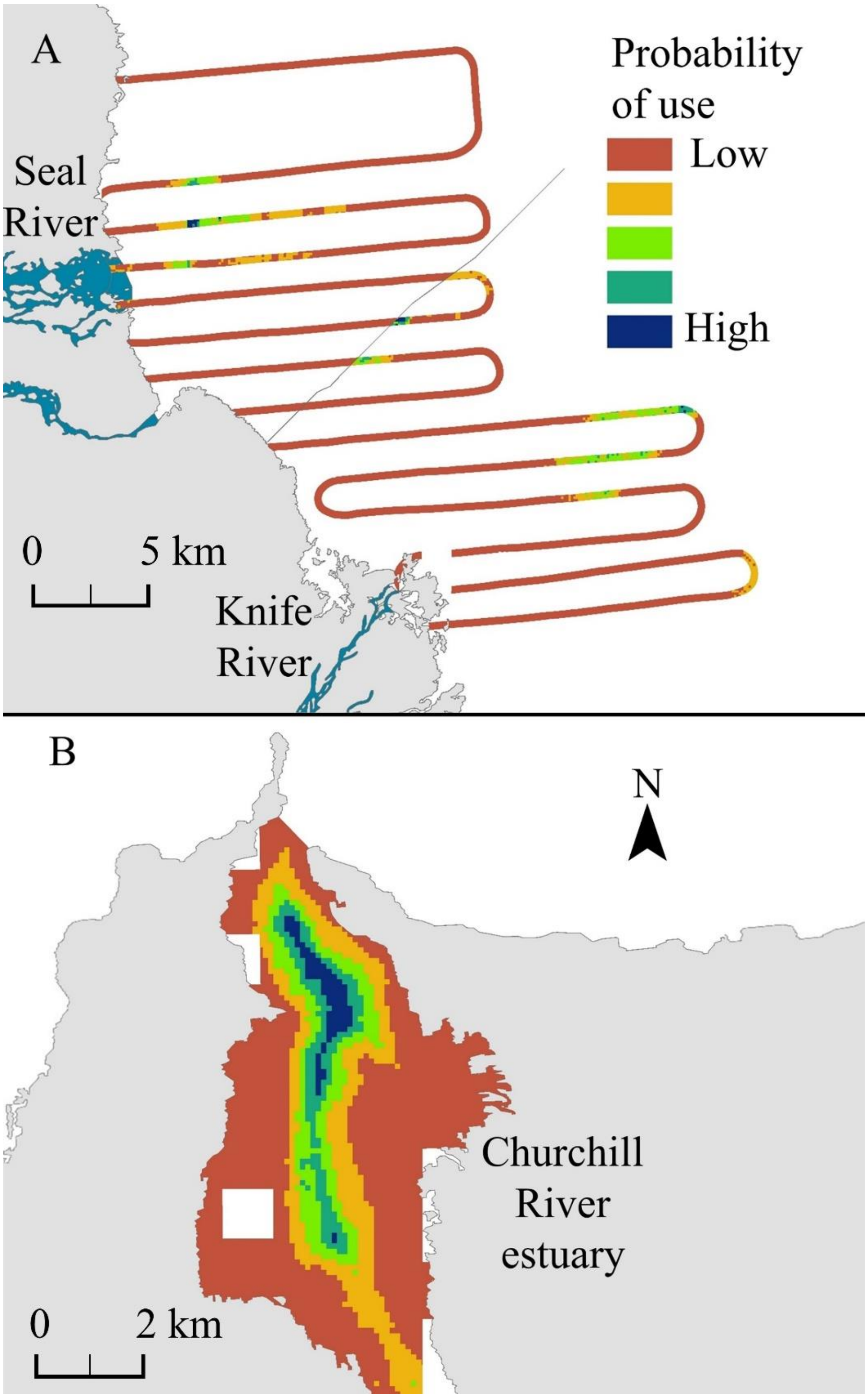


Figure 2. 17 Predicted optimal habitat in the Seal River (A), the Knife River (A) and the Churchill River estuary (B), beluga habitat areas from RSF's. The grey line splits the Seal River and Knife River habitat areas. Blue represents areas with high probability of beluga occupation. White areas were masked areas due to raster missing data.

2.6 Discussion

Through MDA classification of WHB beluga habitat areas by the environmental variables associated with beluga locations, we found 5 distinct habitat areas: the Seal River, the Knife River, the Churchill River offshore, the Churchill River estuary and the Nelson River. Summer WHB beluga habitat is often described in terms of the high occurrence areas of beluga in the Seal, Churchill and Nelson River estuaries and offshore areas, which has influenced the design of aerial surveys for population counts (Manitoba western Hudson Bay ad hoc beluga habitat sustainability plan committee, 2016; Matthews et al., 2017; Richard et al., 1990; Pierre R Richard, 2005). Our results indicate that the Knife River area should also be considered as a high occurrence habitat area for belugas. Habitat differences used in our analysis that contribute to this classification include the distance to river mouth, CDOM concentration, and TSS concentration which all displayed high discriminant scores from MDA (Table 6). MDA of the Seal, Knife, and Churchill areas gave a first discriminant axis showing separation between the Seal and Knife River habitat (Figure 8). The main drivers of the first discriminant axis were distance to shore, and distance to intertidal zones (Table 6). In the Seal River beluga were located closer to the shore and intertidal area than in the Knife River, possibly indicating these areas serve different purposes as belugas select areas closer for bottom rubbing and molting in the Seal River. It's possible that in previous surveys belugas in the Knife River area were found but not interpreted to be separate from the Seal River area, particularly when examining maps of beluga locations created by Richard et al. (2004). An alternative explanation is that the environmental conditions in the Knife River area at the time of our survey resulted in optimal beluga habitat which has been previously unobserved.

In all habitat areas the best resource selection function models included either the distance to river plume or distance to river mouth. Many groups of belugas were found in close proximity to each other around 11 km from the Knife River mouth, a pattern which was also found in the Seal River (at approximately 4.5 km). Beluga associations with rivers or river mouths in summer habitat has been found in multiple populations and is considered to be an indicator of a connection to the river plume, or prey availability (Booy et al., 2021; Hornby et al., 2016; Huntington, 2000; Moore, Shelden, et al., 2000; Rugh et al., 2000; A. J. Smith et al., 2017; T. G. Smith et al., 1994). Freshwater-saltwater mixing zones are areas of high productivity as rivers deliver nutrients and organic matter beneficial for primary and secondary production (Hudon et al., 1996; Le Fouest et al., 2013; McClelland et al., 2012; Tank et al., 2012). Distribution of belugas has been shown to be related to river flow, and the freshwater-saltwater mixing zones in the Cook Inlet, Nelson, and Churchill River estuaries (Hansen 1988; Idle 1989; Smith 2007; Goetz et al. 2012; Smith et al. 2017b). Belugas in Cook Inlet showed preference to rivers with medium and higher flow compared to low flow (Goetz et al. 2007).

By outlining the river plumes for the Seal, Knife and Churchill rivers we investigated if beluga habitat association with river mouths is related to the high nutrient and prey availability from river plumes. The distance to the 50% river CDOM influenced waters was selected as an important variable through BIC model selection in both the Churchill estuary and the Churchill offshore (Figure 6). Distance to the 50% river CDOM influenced water was not chosen for Seal River or Knife River models, which may be due to characteristics of the river plumes or the shoreline. The Churchill plume is larger than the Seal and shows variation with the tide (Figure 2), while the Seal River plume is comparatively small and shows little tidal variation (Figure 3). The Knife River is not monitored for flow, though it is known to be lower than the Seal River. For this reason, and after testing alternative plume delineations using both the Seal River and Knife River starting points, the final delineation was based on a starting point in the Seal River. The Seal and Knife rivers had a large intertidal area which covered a large portion of the habitat. Intertidal areas were not considered when determining river plume boundaries, so beluga and available locations in the intertidal zone were given a distance to the 50% river CDOM influenced water of 1. In the Seal and Knife River, these limitations in river plume delineation likely resulted in models selecting for distance to river mouth in place of river plume.

The water quality indicators of TSS and CDOM were included in the best RSF model for each habitat area. While highly correlated, these environmental variables can represent different habitat conditions for belugas related to turbidity, freshwater inputs, and impacts on primary production which influences prey availability (Frey et al., 2017; Hornby et al., 2017; Sigman & Hain, 2012). TSS can be considered as an indicator of water turbidity, and in western Hudson Bay, both freshwater river inputs and expansive intertidal areas are sources of TSS. CDOM is the colored portion of dissolved organic matter (DOM) that can be used to measure DOM inputs to marine systems from river sources (Hessen et al., 2010; Stedmon & Markager, 2003). Both TSS and CDOM in the water column will result in higher absorption and reflection of light, therefore high concentration areas of TSS and CDOM can represent areas with lower primary production

(Asmala et al., 2018; Aumack et al., 2007; McSweeney et al., 2017). Sediment presence detected by TSS concentration could also indicate a greater nutrient availability from resuspension, which provides nutrients for primary production (Asmala et al., 2018; Schallenberg & Burns, 2004). While DOM blocks the light necessary for primary production of phytoplankton, it can stimulate heterotrophic bacteria production and growth (Andersson et al., 2018). Beluga in western Hudson Bay were found to occupy waters with lower CDOM and TSS than the available range, and all models included negative coefficients for CDOM and TSS showing a selection for lower values (Table 6). While CDOM concentration in all available habitat areas ranged from 0.46 m^{-1} to 21.89 m^{-1}, beluga occupied areas with concentrations between 0.48 m^{-1} and 4.74 m^{-1} (Figure 5a). TSS ranged between 21.99 – 241.59 g/L and beluga occupied areas with TSS between 22.60 g/L and 125.10 g/L (Figure 5b).

Suspended sediment concentration has been studied in relation to beluga habitat use as an indicator of turbidity or freshwater input (Hornby et al., 2016; Moore, Shelden, et al., 2000; Rugh et al., 2000). When examining water turbidity, which was determined through classifying water color of aerial imagery, it was found that beluga preferred low to medium turbidity in the Mackenzie shelf in June 2012, and the opposite relationship in 2013, though this likely resulted from limited available open water (Hornby et al., 2016). The preference for less turbid waters agrees with our results that find beluga select habitat with lower TSS. In the Churchill River, Hansen (1987) found no correlation between beluga estuary presence and turbidity between 1983 and 1986, though this study measured Turbidity in using oceanographic sampling stations measuring turbidity to 3 m depths in Formazin Turbidity Units. Our findings that TSS was an important habitat variable in the Churchill estuary differed from Hansen (1987), which likely stemmed from different sampling technique and measurements. Beluga habitat has not been previously investigated in relation to CDOM concentration.

When multiple habitats are available, the choice for individuals or groups to occupy one or the other based on their benefits is habitat selection. The WHB beluga are philopatric to the summer habitat along western Hudson Bay, but not necessarily philopatric to a specific estuary and show movement between areas (Colbeck et al., 2013; Martin et al., 2001). In the Churchill River area, the best models for the offshore and in estuary habitat areas included different combinations of environmental variables. While both the estuary and the shoreline included distance to river plume as an important characteristic, the offshore area only included CDOM as an additional variable. In the estuary TSS was selected in addition to distance to the intertidal zone combined with shoreline, and SST (Table 6). Beluga estuary use theories have emphasized their importance in predator protection, molting, thermal advantages, and abundance of prey (Finley, 1982; Sergeant, 1973; Sergeant & Brodie, 1969a; A. J. Smith, 2007; St. Aubin et al., 1990). While the offshore Churchill area model includes two variables related to prey detection, the estuary model includes SST and the distance to the intertidal zone combined with shoreline. This may suggest that belugas occupy Churchill offshore areas for feeding and the distribution inside of the estuary is related to feeding in addition to molting, predator protection, and thermal advantages.

High quality or abundant prey availability in western Hudson Bay may contribute to beluga estuary habitat use as a summer feeding ground (Doan and Douglas 1953; Sergeant and Brodie 1975; Watts and Draper 1986). The diet of belugas in the WHB has not been investigated fully, although there have been observations of beluga feeding on capelin, observations of cooperative feeding, and investigations of stomach content from beluga hunted in the Churchill River, found to contain capelin, shrimp and squid (Doan and Douglas 1953; Sergeant 1973; Sergeant and Brodie 1975; Hansen 1988; Watts and Draper 1988). The relationship with river plumes and water quality both represented aspects of productivity and prey availability. The environmental variables of bathymetry and chlorophyll a have also been used to represent prey availability (Hauser, Laidre, Stern, et al., 2017; Hornby et al., 2017; Moore, DeMaster, et al., 2000). Bathymetry was included in the final model for the Nelson River, which indicates some connection to beluga habitat use, although data limitations did not allow us to assess the importance of this indicator for the other habitat areas. Surface chlorophyll a is a green pigment within phytoplankton which can be measured on the water's surface using ocean color satellites (Frey et al., 2017; Sigman & Hain, 2012). In ice-free areas of Hudson Bay primary production comes from phytoplankton, and so chlorophyll a has been used to represent the biomass of primary producers, and prey availability for beluga (Frey et al., 2017; Hornby et al., 2017). Beluga seeking prey would be expected to be found in locations with higher chlorophyll a concentration, and this environmental variable was selected for the final model in all but the Churchill River offshore and in estuary areas. However only in the Seal River area was there a positive coefficient for chlorophyll a, which represents beluga preference for areas with higher chlorophyll a.

This analysis included the habitat variables of SST, distance to shore, and distance to intertidal areas as representative of estuary use theories of beluga using habitat optimal for molting through mudflat areas and warmer waters from rivers which give thermal advantages, as well as predator protection from killer whales as they cannot access shallow shoreline areas (Finley, 1982; Matthews et al., 2017; Pierre R Richard, 2005; Sergeant, 1973; Sergeant & Brodie, 1969a; A. J. Smith, 2007; St. Aubin et al., 1990; Westdal et al., 2016). Habitat modeling has shown that the environmental features related to beluga molting, which include salinity level, water temperature, and relationships with mudflats/intertidal areas, impact the distribution and abundance of beluga in summer estuary habitat (Ezer et al., 2008; Goetz et al., 2007, 2012; Hornby et al., 2017; A. J. Smith et al., 2017). Belugas moved farther into the warm waters of the Churchill and Mackenzie River estuaries when colder coastal water temperatures were recorded (Hansen 1988, Scharffenberg et al. 2019). Inclusion of the distance to shore, distance to intertidal areas and sea surface temperature in the final model for each habitat area was variable (Table 6). Use of habitat for predator protection or molting would vary based on conditions and timing, as areas close to the shoreline would only be used when killer whales are present, or intertidal areas would only be used when belugas are rubbing. It may not be possible to capture these relationships in one aerial photographic survey. Under the estuary use theory belugas would prefer warmer waters for thermal advantages, which may show less temporal variation and could be more detectable under our modeling design. In the Seal River area and the Churchill River estuary, SST was included in the final model where beluga prefer warmer waters (Table 6).

Our research was limited by the availability, resolution, and quality of cloud free satellite imagery on the dates of aerial surveys, which was managed through interpolating missing pixels in chlorophyll a rasters, using the closest available dates for MODIS imagery, and taking averages of sentinel 2 data in the month before and after survey dates. Despite this TSS or CDOM were important in all models and show potential for descriptions of beluga habitat use in the future. Measurements of surface concentration of chlorophyll a, TSS and CDOM concentration are not a perfect representation of light availability, nutrient availability, and resulting phytoplankton biomass and primary productivity. Other factors such as stratification, weather, mixing of water layers from winds and currents, tide, salinity, and how primary productivity equates to secondary production and overall availably of prey resources impacts overall distribution and production in estuaries (Azhikodan & Yokoyama, 2016; J. E. Cloern et al., 2014; James E. Cloern, 1987; McSweeney et al., 2017). They can be however used to represent these concepts in an area where prey distribution and other habitat variables are not known completely, as is the case in western Hudson Bay (Ferland et al., 2011; Sigman & Hain, 2012). Advances in remotely sensing of oceanographic characteristics has the high potential to contribute to the study of marine mammals which are complicated by their long life, migratory patterns, remote habitat, and limited time spent at the water's surface. Belugas and narwhals can be identified and located using satellite imagery (Charry et al. 2021). Though Charry et al. (2021) made use of high-resolution images, multispectral bands can also be purchased, allowing for calculations of habitat data such as TSS and CDOM with collection of beluga location.

2.6.1 Management Implications

This paper models beluga distribution in the WHB with respect to environmental variables related to estuary use theories, including variables previously uninvestigated. The river influenced (distance to river plume, distance to river mouth) and water quality (TSS and CDOM) environmental variables were included in every model across habitat areas. This showed a strong relationship between beluga summer habitat use, rivers, and prey. Other variables show up inconsistently across habitat areas, suggesting that habitat selection for these variables is a secondary occurrence that may vary by location and conditions. To our knowledge this is the first study evaluating beluga habitat using river plume boundaries, TSS, and CDOM. Additionally, the Knife River should be considered as a separate unit for planning of future counts and beluga management. Greater understanding of the current relationship between WHB belugas and their habitat will contribute to effective population management and provide a baseline of habitat use by beluga given expected climate changes. By modeling beluga habitat in western Hudson Bay, we contribute to beluga estuary use theories, improve understanding of important habitat locations for beluga within western Hudson Bay, and determine which available environmental characteristics are associated with beluga distribution patterns.

Connecting text

In the previous chapter, the important environmental characteristics for WHB beluga summer habitat use were investigated. Optimal habitat areas found in this analysis includes the Churchill River estuary. The town of Churchill, Manitoba is an ecotourism center, and tourists from around the world travel to Churchill in the summers to see belugas. Tourist vessels include motorboats, zodiacs, paddleboards, and kayaks, which congregate on the estuary for whale watching activities. The next chapter will cover the impacts of whale watching on belugas in the important habitat of the Churchill River estuary.

3 Chapter 3: Beluga (*Delphinapterus leucas*) response to personal watercraft and motorized whale watching vessels in the Churchill River estuary

This chapter has been submitted to Frontiers in Marine Science under the following title and authors:
Ausen, E., Marcoux, M., Chan, W., Barber, D. Beluga (*Delphinapterus leucas*) response to personal watercraft and motorized whale watching vessels in the Churchill River estuary

3.1 Abstract

As interest in tourism and conservation grows worldwide, whale-watching has become a popular means of educating the public about wildlife conservation. The short-term impact of ecotourism industries on observed species has been widely studied with findings that indicate responses are most often behavior alterations or avoidance. Close vessel interactions with beluga whales (*Delphinapterus leucas*) are a major draw for whale-watching ecotourism in Churchill, Manitoba, Canada. As the Churchill River estuary and surrounding waters are assessed for a Marine Protected Area, information on the response of belugas to vessels are needed to inform management. To assess this, an oblique time lapse camera system with a 5-minute photo interval was set up overlooking a section of the Churchill River estuary that is shared by belugas and tourist vessels. Measurements calculated from photos were used to compare the distance between belugas and kayaks, motorboats, paddleboards, and Zodiac whale-watching vessels. These distances were compared to an expected distribution generated from locations of surfacing belugas captured by the camera without the presence of vessels. We found evidence that belugas show attraction to kayaks, avoidance to paddleboards, and distribute independently from Zodiacs and motorboats. This is the first study to quantify the behavioral response of cetaceans to tourist vessels using a camera system and a distance-based analysis. Results could inform the creation of a site-specific management system that accounts for beluga-vessel relationships.

3.2 Introduction

Whale-watching is known for increasing tourist investment in conservation, providing research opportunities and creating alternative economic activities to resource exploitation, including whaling or whale removal for aquariums (Peter J Corkeron, 2004). Intensity of tourism, vessel type (Pirotta et al., 2015), vessel maneuvering (Argüelles et al., 2016; Arias et al., 2018; Filby et al., 2014), management regulations (Tosi & Ferreira, 2009) and vessel compliance to regulations impact cetacean response (P. J. Corkeron, 1995; Hoarau et al., 2020; Stamation et al., 2010). Tourism industries should therefore be closely monitored as energetic costs associated with whale behavioral reactions can affect the fitness and survival of a population (Bejder, Samuels, Whitehead, Gales, et al., 2006; Christiansen et al., 2013a, 2013b, 2014; Currie et al., 2021; D Lusseau et al., 2006; David Lusseau & Bejder, 2007; Williams et al., 2006b).

Studies on ecotourism industries worldwide have found that whales from different populations respond to tourist vessels through behavior changes. Behavioral response is often recorded as alterations in the time spent traveling, foraging, or resting in the presence of tourism vessels (Arcangeli & Crosti, 2009; Avila et al., 2015; Rochelle Constantine et al., 2004; Coscarella et al., 2003; Dans et al., 2012; David Lusseau et al., 2009; Steckenreuter et al., 2012; Stockin et al., 2008; Visser et al., 2011; Williams et al., 2006b). Changes to respiration or blow rate (Christiansen et al., 2014; Schuler et al., 2019), altered surfacing behaviors (Coscarella et al., 2003; Hastie et al., 2003; Lemon et al., 2006; Noren et al., 2009; Stamation et al., 2010), increased erratic movements (Avila et al., 2015; David Lusseau, 2006; Stensland & Berggren, 2007), and shifts in group size or dispersion (Bejder et al., 1999; Bejder, Samuels, Whitehead, & Gales, 2006; Steckenreuter et al., 2012; Tosi & Ferreira, 2009) have also been observed as a response to vessel presence. While the majority of whale-watching vessel interactions indicate impacts to the observed species, the responses vary by population (Senigaglia et al., 2016), age class composition of pods (Magalhães et al., 2002; Stamation et al., 2010; Steckenreuter et al., 2012), and sex (David Lusseau, 2003b; Williams et al., 2002) of the targeted species.

Whale and dolphin response to tourism vessels in close range is complicated as both attraction and avoidance behaviors have been recorded. Avoidance includes distancing by cetaceans both as vertical movement underwater through dives (David Lusseau, 2003b; Stamation et al., 2010), and horizontal movement away from vessels (Steckenreuter et al., 2012). Reduced path directiveness in travel, changes in travel direction (Amrein et al., 2020; Lemon et al., 2006; Richter et al., 2006), increasing swimming speed (Avila et al., 2015; Magalhães et al., 2002; Scheidat et al., 2004) and combinations of these behaviors are considered horizontal avoidance of vessels by cetaceans (Bejder, Samuels, Whitehead, & Gales, 2006; Currie et al., 2021; Kruse, 1991; Santos-Carvallo et al., 2021; Schuler et al., 2019; Stamation et al., 2010; Williams et al., 2002, 2009). Attraction, interaction, positive reactions, and approach are terms that have been used to describe similar behaviors of cetaceans approaching vessels, traveling with vessels, and swimming around or underneath tourism vessels (Arcangeli & Crosti, 2009; R. Constantine, 2001; Filby et al., 2014; Gregory & Rowden, 2001; Hoarau et al., 2020; Malcolm & Penner, 2011; Stamation et al., 2010; Steckenreuter et al., 2012). For instance, dwarf minke whales (*Balaenoptera acutorostrata*) in Australia were observed more than expected within 60 meters of swim-with-whale tourism boats indicating attraction (Mangott et al., 2011). Independent or neutral reactions, described as no change in cetacean behavior in the presence of tourism vessels have been recorded along with attraction and avoidance (Arcangeli & Crosti, 2009; R. Constantine, 2001; Filby et al., 2014; Gregory & Rowden, 2001). Attraction behaviors and neutral responses to tourist vessels have been grouped together for humpback whales (*Megaptera novaeangliae*) to better understand avoidance rates in Reunion Island, and Vava'u, Kingdom of Tonga, finding avoidance 27.4% and 33.5% of the time, respectively (Fiori et al., 2019; Hoarau et al., 2020).

Churchill, Manitoba, Canada, is known for the unique whale-watching interactions with the Western Hudson Bay beluga whales (*Delphinapterus leucas*) that occupy the estuary from June to September every year. The yearly return of beluga whales to estuary habitat in the summer has been hypothesized to be related to matrilineally learned philopatry, or biological advantages associated with greater prey availability, optimal habitat for molting and predator protection (Finley, 1982; Sergeant, 1973; Sergeant & Brodie, 1969a; A. J. Smith, 2007; St. Aubin et al., 1990). In the Churchill River estuary, beluga are perceived to have a unique response to small boats, such as kayak and Zodiac whale-watching tours, often displaying interactive behavior that is a major draw for ecotourism to the region (Malcolm & Penner, 2011). While this behavior has been described in observational studies, direct measurement of beluga response would provide needed information for tourism management that meets the needs of tour operators and mitigates against harmful disturbance to the whales. In this paper, we used time-lapse photography to identify surfacing beluga in a section of the estuary and calculate the distances between belugas and tourist vessels. Through comparison of beluga-vessel relationships to beluga habitat use without vessel presence we can determine if belugas are closer to, further from, or the same distance to vessels than would be expected. In other words, we can use the distance between belugas and vessels to determine if belugas are attracted to, avoid, or are independent from different types of tourist vessels in the Churchill River estuary. Because of the perception of the Churchill community and tour operators as well as relevant literature, we expect to find belugas are attracted to tourist vessels in the Churchill River estuary (Malcolm & Penner, 2011; Manitoba western Hudson Bay ad hoc beluga habitat sustainability plan committee, 2016; The Churchill Beluga Whale Tour Operators Association et al., 2015).

3.3 Materials and Methods

3.3.1 Study site

This study took place in the Churchill River, an enclosed subarctic estuary with a diurnal tide system that empties into the Hudson Bay (Figure 3.1), from July 23rd to September 18th, 2020. For this study we used photos taken between August 13th and August 28th, 2020. During August 2020, the difference between high and low tide was 4 meters. Daily activity on the Churchill River estuary includes whale-watching boats, scientific vessels, fishing vessels and local pleasure crafts. The vessel type and quantity on the estuary vary daily with tourist demand as well as weather. Larger groups of kayaks and paddleboards, as well as accompanying Zodiacs (inflatable boats capable of carrying multiple passengers with a single motor) are present in the estuary at low tide when waters are calm. During falling, rising and high tide, motorboats (solid hull boats capable of carrying multiple passengers with a motorized propulsion system) and Zodiacs are the most frequent vessels. The year of this study was different from a typical year in that there were fewer international tourists due to travel restrictions from the COVID 19 pandemic.

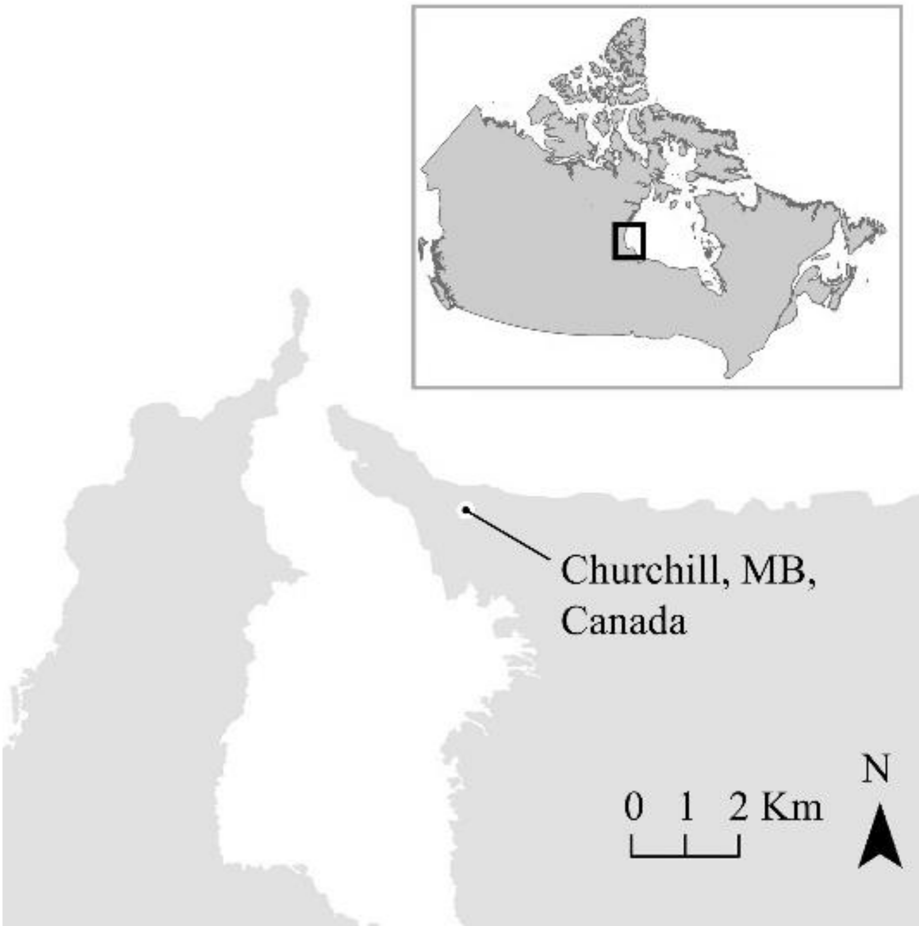


Figure 3. 1 The Churchill River estuary in the Hudson Bay.

3.3.2 Setup

A Harbotronics Cyclapse Pro- Glacier time-lapse camera system, with a Harbotronics Digisnap Pro time-lapse controller, and a Pentax K1 Mark II camera with Pentax HD PENTAX-D FA 28-105mm f/3.5-5.6 ED DC WR Lens was installed on the 2nd floor of the Port of Churchill Gallery (Figure 3.2). The camera was set up facing west, and the lens was set to a focal length of 58 mm to capture the horizon and most of the estuary. To optimize photo quality in an outdoor setting with varying light, the ISO speed was set to 800, exposure to 1/1600 seconds, and f-stop to 11. Photos were taken every 5 minutes from 6:30 am to 8:30 pm every day.

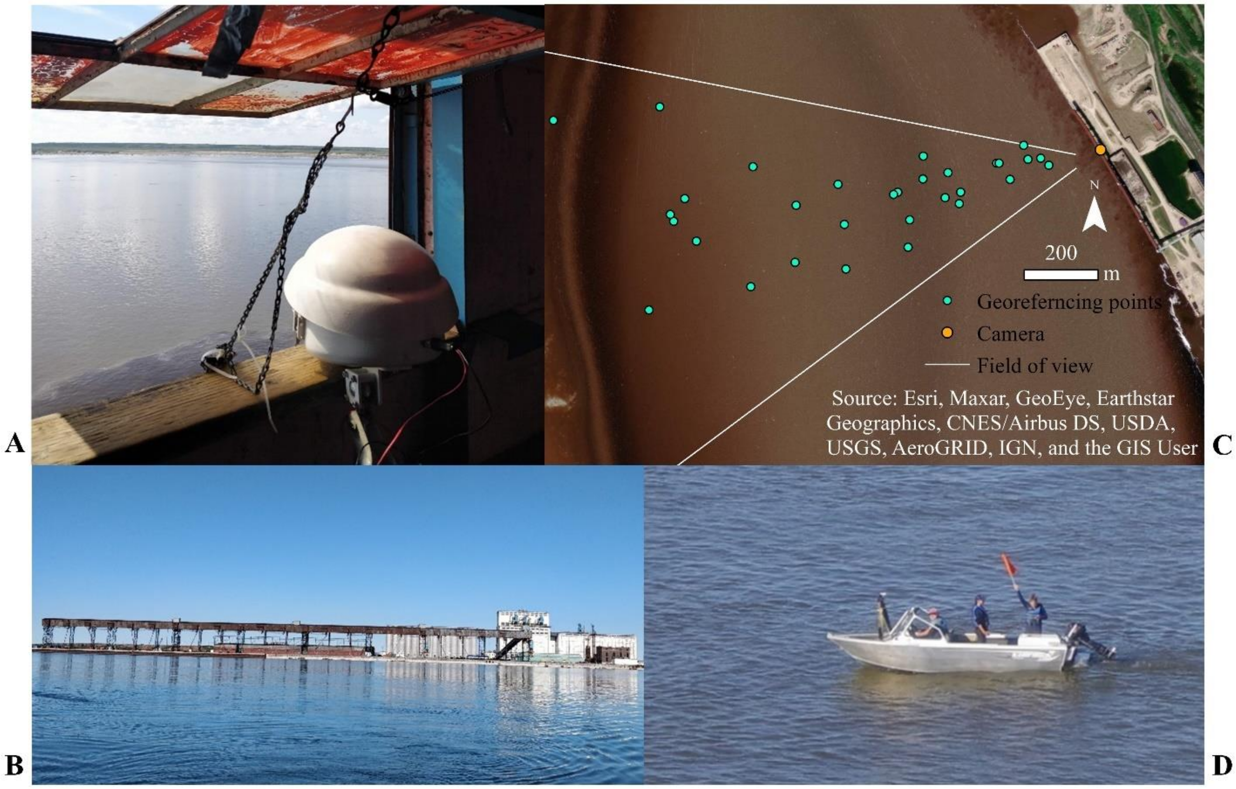


Figure 3. 2 (A) Digisnap Pro Cyclapse system. (B) The gallery of the port of Churchill from the estuary. (C) Location of georeferencing points on the estuary (within the white lines representing field of view of the camera). (D) Image of a georeferencing point being taken.

To calibrate and test distance measurements from photos, 30 georeferencing points were taken over 5 days (Figure 3.2). A Garmin GPSMAP 64s was used to take these georeferencing points, which has a 5-15m error depending on satellite orientation (https://support.garmin.com/en-CA/?faq=aZc8RezeAb9LjCDpJplTY7). Georeferencing points were taken following Pavia et al (2015) by maneuvering a boat into view of the camera, with one individual in the boat holding up an orange flag and taking a simultaneous GPS point with the time-lapse camera photo (Paiva et al., 2015). Technical errors with the camera system resulted in camera angle and field of view shifts, so accurate measurements could only be obtained from photos between August 13th and August 28th, 2020. Images were first corrected for pincushion lens distortion using the Pentax filter in Photoshop 21.2.0.

3.3.3 Camera errors

The camera system was designed to receive power from a wall outlet in the gallery using a AC power converter from Harbotronics. Within a week of camera setup on July 23rd, the system stopped working as intended. A backup system was available to replace the original setup, however when in place the AC power chord no longer worked to charge the camera battery. Every one to two days the camera battery was replaced with a charged battery, by removing the camera from the tripod and replacing the camera after. Photos were inspected using GNU Image Manipulation Program version 2.99.2 (GIMP). When these photos were inspected, it was revealed that the removal and replacement of the camera resulted in small changes in the field of view (< 21 x or y pixels). By overlaying images from different dates in GIMP the field of view shifts and dates were recorded (Table 3.1, Figure 3.3). Larger shifts in the field of view occurred several times due the tripod being knocked out of place. This inspection was done before photos were corrected for lens distortion. The georeferencing points taken covered field of view shifts of up to 20 pixels (table#). The distance equations used all georeferencing points from shifts in field of view up to 20 pixels, allowing for photos between August 13th, 2020 at 11:55 AM and August 28th, 2020 at 10:45 AM to be used in analysis (field of view 7 through 14).

Table 3. 1 The dates for photos used in analysis with the shift in field of view from the previous day represented in x and y pixels. This table includes the number of georeferencing points from each field of view (FOV) shift.

	Pixel shift			Georeferencing points	
Date	x	y	FOV	All	<700 y pixels
8/13/2020	22	-52	7		
8/14/2020			7		
8/15/2020	-10	10	8		
8/16/2020	17	-10	9		
8/17/2020			9	7	4
8/18/2020	3	3	10	3	1
8/19/2020			10	8	5
8/20/2020	3	-4	11		
8/21/2020			11		
8/22/2020			11	7	5
8/23/2020	-20	18	12	4	2
8/24/2020	-4	1	13		
8/25/2020			13		
8/26/2020	1	1	14		
8/27/2020			14		
8/28/2020	-179	15	15		

Figure 3. 3 Image overlay between a photo from August 15 and August 16th. When the camera battery was changed the field of view shifted by 17 x pixels and -10 y pixels (FOV 8 to 9).

3.3.4 Measurements

Photogrammetry of oblique imagery is characterized by the change of scale associated with increasing distance from the measurement device. To reference oblique imagery, surface elevation, the location of the camera, and the camera specifications are needed (Höhle, 2008). It was assumed that the elevation of the area remained constant to the height of the camera and tide. Height of the camera and of the port above water level were measured using a weighted rope. Tide level measurements were obtained from the Canadian Hydrographic Service gauge (station 5010, https://www.qc.dfo-mpo.gc.ca/tides/en/tide-and-water-level-station-data) measured every 3 minutes. The angle of the camera relative to vertical was approximately 79 degrees when measured during set up and removal using the Clinometer smartphone app from PixelProse SARL.

The area captured by a photo is determined by the distance of the object from the camera and lens angle of the camera which is also called field of view (FOV) (Figure 3.4). The focal length (f), the horizontal sensor length (s_h) and vertical sensor lengths (s_v) are camera specifications that are used to determine both horizontal field of view (Θ_{HFOV}) and vertical field of view (Θ_{VFOV}) using equation (1) and (2) (Havens and Sharp, 2015). The Pentax K1 Mark 2 camera has a horizontal sensor length of 35.9 mm and a vertical sensor length of 24 mm.

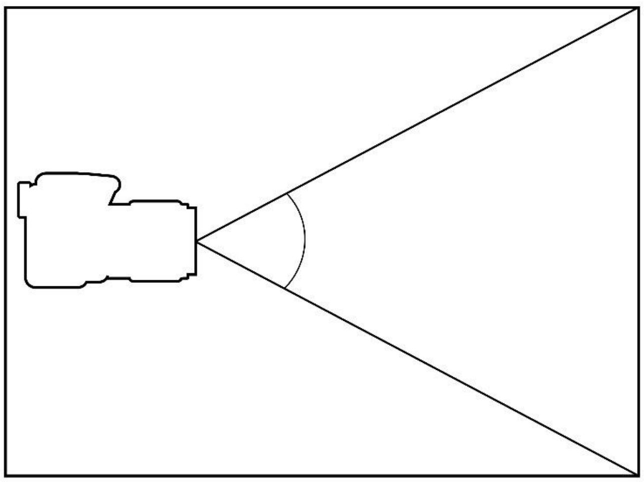


Figure 3. 4 Vertical field of view of the camera (Θ_{VFOV}).

$$\Theta_{HFOV} = 2tan^{-1}(s_h/2f) \quad (1)$$

$$\Theta_{VFOV} = 2tan^{-1}(s_v/2f) \quad (2)$$

Measurements were obtained through calculations based on the pixel dimensions of the photos. Each 17.9 MB image contained 7360 by 4912 pixels (Figure 3.5). Horizontal pixels are considered as x pixels and vertical as y for the following calculations. The origin of the image at 1,1 is located at the top left corner. The center of the image, known as the principal point (P) is assumed to approximately represent x = 3680 and y = 2546. The limits of the horizontal field of view of the camera are at x = 1 and x = 7360. The real-world area of each pixel increases as you move from y = 4912 at the bottom of the photo to y = 1 at the top, so the area between 1 and 7360 x pixels increases with distance from camera. A pixel location (x,y) on the photo will be represented by the point E, and E' in the real-world (Figure 3.6). An x pixel has an angle from the camera (O) subtended by the arc of the center line of the camera ($\overline{OB}$) to any given pixel location ($\overline{OE}$) (Figure 3.6). This angle (Θ_x) can be determined if the distance between E at a given y pixel value and the vertical center line (x = 3680) is known in pixels. To achieve a representation of that distance, the horizontal field of view (Θ_{HFOV}) and ½ of the image width in x pixels ($\overline{AB} = 3680$) were used in conjunction with trigonometric laws in equation 3.

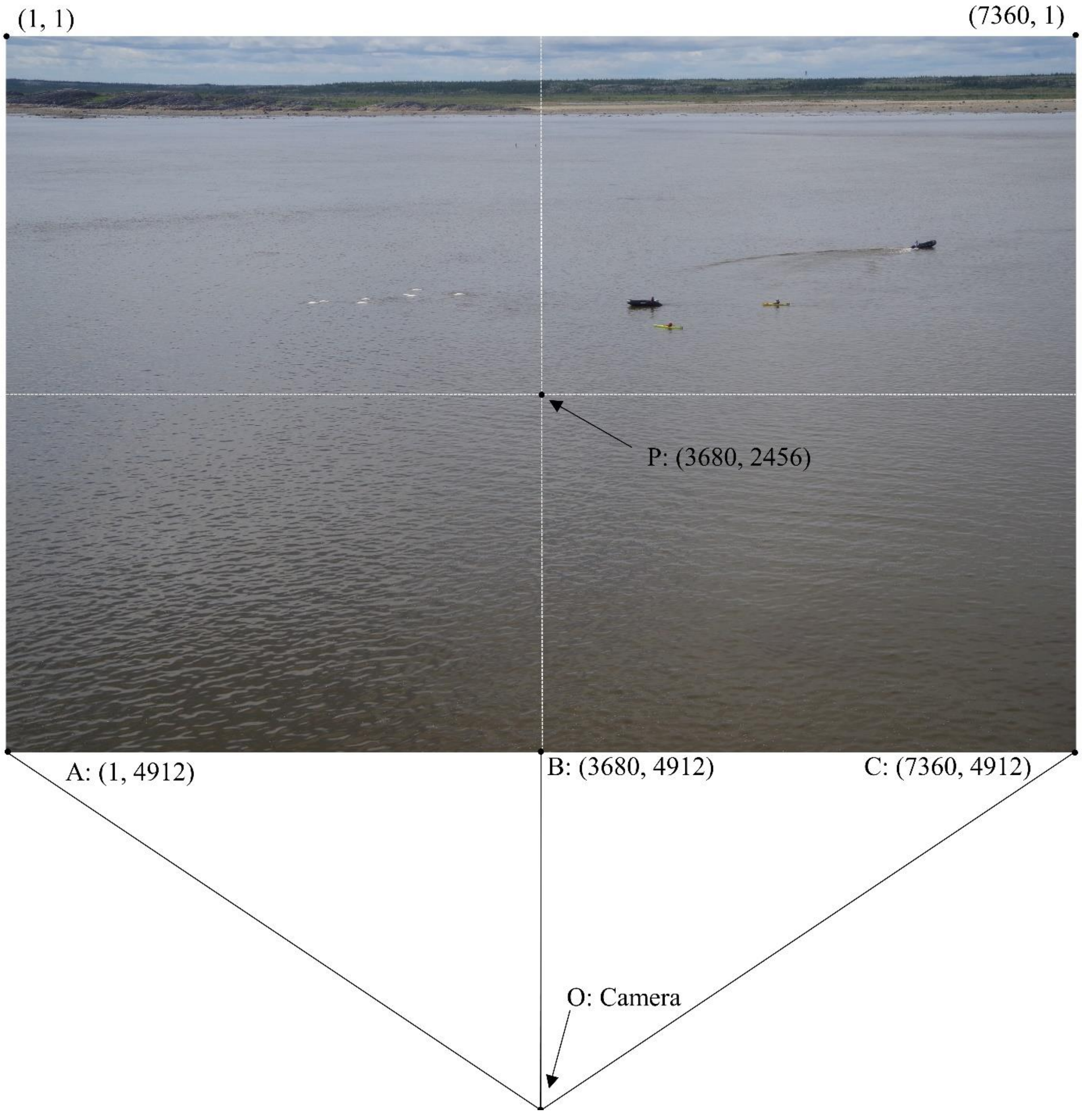


Figure 3. 5 Image dimensions in x, y pixels. Points A, B, C, and P are labeled for understanding of translation between real world and image calculation. O is the camera location.

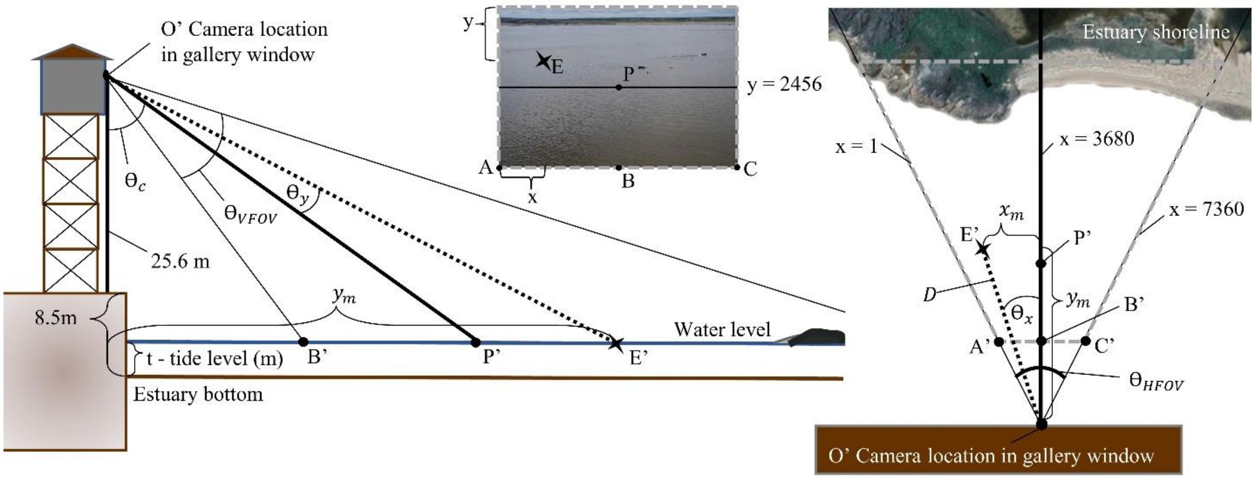


Figure 3. 6 Side view (left) and bird's eye view (right) of camera set up in the Port of Churchill gallery. Location of multiple points on an oblique photo (A, B, C, P) are represented in this diagram (A', B', C', P') to translate between the image and real-world calculations. The star (points E and E') shows how a location in the real-world would be found on a photo with pixel coordinates at (x,y).

$$\overline{OB} = \frac{\overline{AB}}{\tan\left(\frac{\Theta_{HFOV}}{2}\right)} \quad (3)$$

When the length of $\overline{OB}$ is known, Θ_x for any x pixel value can be calculated (equation 4). This angle (Θ_x) remains the same for a given x-value and is not impacted by different y or increasing distance of real-world locations from the camera (equation 4).

$$\Theta_x = tan^{-1}\left(\frac{x-\overline{AB}}{\overline{OB}}\right) \quad (4)$$

The vertical dimension of the image in y pixels can be understood in the same way using VFOV (Figure 3.6). The distance from the camera to the principal point ($\overline{OP}$) (equation 5) is used to determine the angle from the camera subtended by pixel y at E ($\overline{OE}$) and $\overline{OP}$ (equation 6).

$$\overline{OP} = \frac{\overline{BP}}{\tan\left(\frac{\Theta_{VFOV}}{2}\right)} \quad (5)$$

$$\Theta_y = tan^{-1}\left(\frac{\overline{BP}-y}{\overline{OP}}\right) \quad (6)$$

These calculations allow for the angle from camera between the principal point (P) of the image to both the x pixel (Θ_x) and y pixel (Θ_y), to be determined (Figure 3.6).

The height of the camera above water level (h) is the sum of the height of the camera in the gallery above the port floor (25.62m) and the distance from the port floor to the bottom of the estuary (8.51m) subtracting the estuary water level (equation 7). Using the above angles (Θ_x, Θ_y), the height of the camera above estuary water level (equation 7), and the angle of the camera from nadir (Θ_c), distances to and between pixels can be calculated (Figure 3.6). The right angle subtended by the intersection of the vertical line at x = 3680 pixels and any horizontal line at a y pixel value allows for distance calculations between the camera and real-world locations using the Pythagorean theorem. Distance in meters between the y pixel of the real-world object at x = 3680 (y_m) is calculated using equation 8. The distance in meters from x = 3680 to the real world value of x uses y_m and Θ_x in equation 9, and the distance from the real world object at a pixel (x,y) to the camera (D) location represented at the same elevation as the tide level is then calculated using equation 10. The law of cosines can then be used to determine the real-world distance between two pixels (equation 11).

$$h = 25.62 + (8.51 - water\ level) \quad (7)$$

$$y_m = h * \tan(\Theta_c + \Theta_y) \quad (8)$$

$$x_m = y_m \times \tan(\Theta_x) \quad (9)$$

$$D = \sqrt{y_m^2 + x_m^2} \quad (10)$$

$$distance\ between\ points = \sqrt{D_1^2 + D_2^2 - (2\ x\ D_1\ x\ D_2\ x\cos(\Theta x_1 + \Theta x_2))} \qquad (11)$$

The exact camera angle at the time georeferencing points were taken was not known due to shifts in the camera position resulting from system errors. The vertical angle of the camera (Θ_c) was determined by splitting the georeferencing points into training and testing groups. Evaluation of the accuracy in determining pixel distances from the camera and visual inspection of images resulted in a cut-off line at y = 700 pixels, above which belugas can be identified and calculations of distances are accurate. Of the 30 georeferencing points, 17 were located over 700 y pixels and these were split into 10 training and 7 testing. GPS locations were entered into ArcGIS and the NEAR tool calculated each distance to the camera location and to other GPS points. The camera angle was determined to be 79.41 degrees using the 10 training georeferencing points by comparing between calculations using equation 9 and GPS distances to the camera. The mean difference in distance to camera between the 7 testing GPS and calculated georeferencing points was 6.6 meters (between 1.7 and 10.0 m). Calculation accuracy was verified by comparing the distances between the GPS locations for the 7 testing georeferencing points and the calculated distance using equation 9 (Figure 3.7). For the 20 distances root mean square error was 4.2 meters. This error can likely be attributed to GPS error, and boat movement with tide as the photo and georeferencing point were taken.

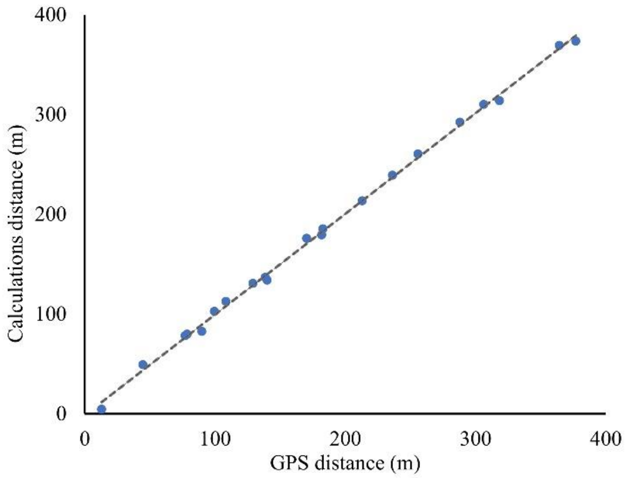


Figure 3. 7 The distances between georeferencing points (m) as determined by inputting GPS locations into ArcMap (x) and by calculating using equations described in this paper (y).

3.3.5 Photo analysis

Belugas and tourist vessels were identified in photos by searching in five horizontal bands of 1,000 y pixels to ensure no objects were missed. For each beluga and vessel, the center location was recorded in x and y pixels. Tide for each photo was assigned to the nearest three-minute Canadian Hydrographic Service tide gauge measurements. Photos were also categorized by tide category, which was determined through equal division in time between minimum and maximum tide as recorded by the Canadian Hydrographic Service gauge. This resulted in tide categories for High, Low, Falling and Rising tide of approximately 3 hours each. If belugas were in a group, defined as swimming in the same direction within approximately two body lengths of each other, one beluga was selected for each to avoid pseudoreplication (Hurlbert, 1984). Each tourist vessel was identified as a Zodiac, kayak, paddleboard, or motorboat. Unique cases such as canoes were also identified, but not included for consideration in this study as there were few occurrences (n = 3).

3.3.6 Analysis

The relationship between belugas and vessels was investigated through measurements of the distance between them. These relationships may be impacted by tide or vessel type (kayak, Zodiac, motorboat, paddleboard), so differences were assessed using a Kruskal-Wallis chi-squared test. A Monte Carlo analysis was performed to generate an expected distribution of distances that would occur if vessels had no effect on beluga distribution. This analysis allowed for a large random sample to be created and for analysis to be iterated multiple times to ensure accuracy. By comparing observed distances to the expected distances between belugas and vessels, each observed distance relationship was classified as closer to, further from, or independent of vessels.

In photos that captured both vessel and beluga locations the distances between belugas and vessels were measured as the observed sample. Each beluga captured in a photo was treated as an independent individual as the 5-minute photo interval did not allow for tracking of individual beluga movement through time. In the 5-minute interval, there was a large change in photo composition, and we assume that different belugas were seen in consecutive photos. Beluga locations in photos without vessels present were compiled and categorized by tide category to make up the expected locations samples (thereafter referred to as expected beluga locations). This was done for two reasons: First, beluga select habitat locations within the Churchill River estuary based on tide, prey movement and other concomitant environmental variables (Caron & Smith, 1990; Chernetsky et al., 2011; Hansen, 1988). By randomly sampling from surfacing beluga captured on the photograph, the expected distribution represents locations that belugas occupy without vessel presence, which allows for more meaningful comparison. Second, there is a detection function associated with correctly identifying beluga in the oblique photographs (Rowcliffe et al., 2011). Beluga further from the camera are less likely to be correctly identified and recorded than those closer to the camera. Sampling randomly from identified belugas for comparison minimizes detection bias.

To test for tide category and vessel type differences in the distance between vessels and beluga, a Kruskal-Wallis chi-squared test was used. For each photo, 100 expected locations were chosen with replacement. Monte Carlo simulations were used to find the expected distribution of distances between belugas and vessels that, due to high numbers of generated points, is close to what should be expected without vessels. The distances between each expected location and all vessel locations were compared to observed distances between beluga and all vessel locations captured in a photo (Figure 3.8). These distances were differentiated by vessel type: kayak, Zodiac, motorboat, or paddleboard. The null hypothesis that observed distances between belugas and vessels were greater than or less than expected distances between belugas and vessels was tested. We chose to categorize beluga behavior as attraction if beluga were found closer to vessels than expected. Avoidance is found if beluga are found further from vessels than expected. Independence was found if observed beluga were not closer to or further from vessels than expected.

A

B

Figure 3. 8 (A) Distances for Monte Carlo analysis collected between beluga and all vessels capture in a photo (white lines). (B) An example of 100 expected locations generated onto the photo (white x), of which the distance between each point and all vessels is used as part of the expected distribution.

Analysis was completed in R (version 4.1.1) using the tidyr and ggplot2 packages (R Core Team, 2021; Wickham, 2016, 2021). The code used for this analysis is available upon request to the authors. One-sided non-parametric Wilcoxon Rank sum tests were used to test if observed distances where greater, or less than expected distances, with a significant p-value of 0.05. This test was selected as distances were not normally distributed. Independence was found if one sided tests showed observed and expected values were not significantly different. This analysis was iterated 100 times, each time determining if beluga show attraction, avoidance, or independence to kayaks, motorboats, paddleboards, and Zodiacs. Results from this analysis were verified by testing for edge effects.

3.4 Results

Between August 13 and August 28th, 2020, 2,303 georeferenced photos were captured of the Churchill River estuary. Of these photos, 262 contained vessels and 1,074 contained beluga (Figure 3.9). Beluga in these photos were captured at all tides, with a total of 2,261 recorded. Of these, 162 photos captured beluga with kayaks, motorboats, paddleboard and/or Zodiacs. These photos contained a total of 29 groups of belugas, 329 individual belugas, 320 kayaks, 43 motorboats, 392 paddleboards and 119 Zodiacs (Figure 3.10). Belugas were found to be distributed between 3.6 and 744.6 meters from all vessels, with a median observed distance of 227.8 m and a mean of 268.3 m (n = 2,005, sd = 164.5) (Figure 3.11). Kruskal-Wallis tests of observed distances between vessels and belugas showed significant differences according to tide (p-value= 0.01, chi-squared = 10.83, df = 3) and vessel type (p-value = <.01, chi-squared = 35.26, df = 3) (Figure 3.12**)**. When testing distances for differences by each vessel type for tide, only paddleboards significantly differed between rising (n=12) and low (n=920) tide.

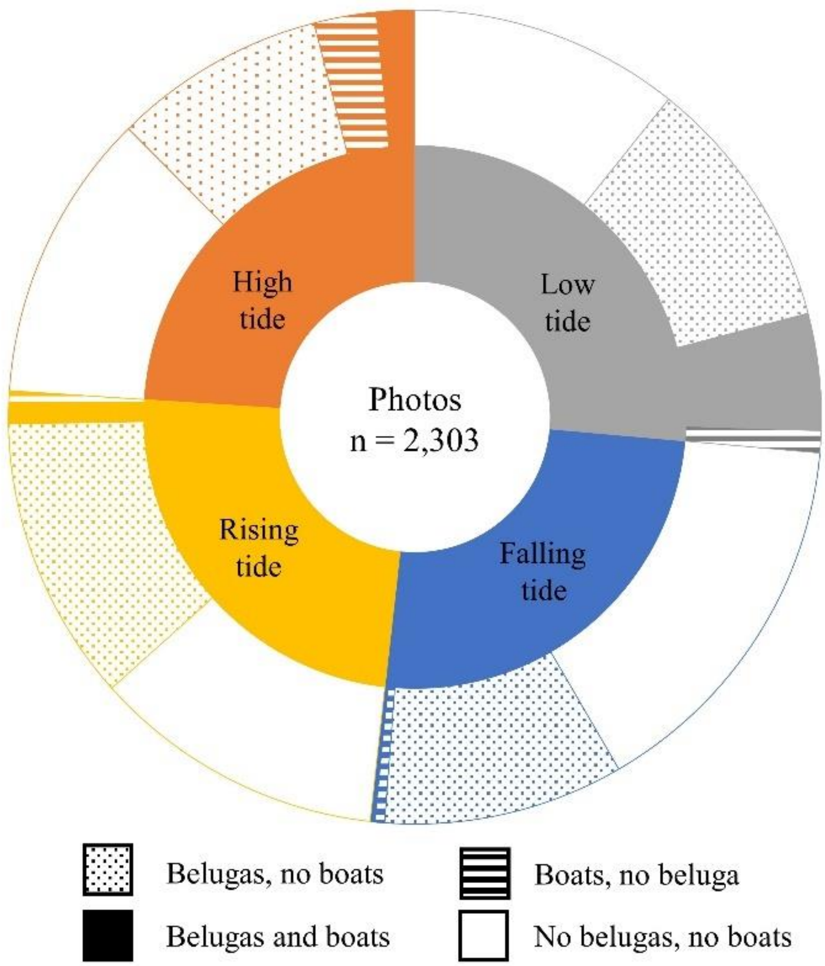


Figure 3. 9 Proportion of photos that captured beluga, boats, and both at each tide catergory.

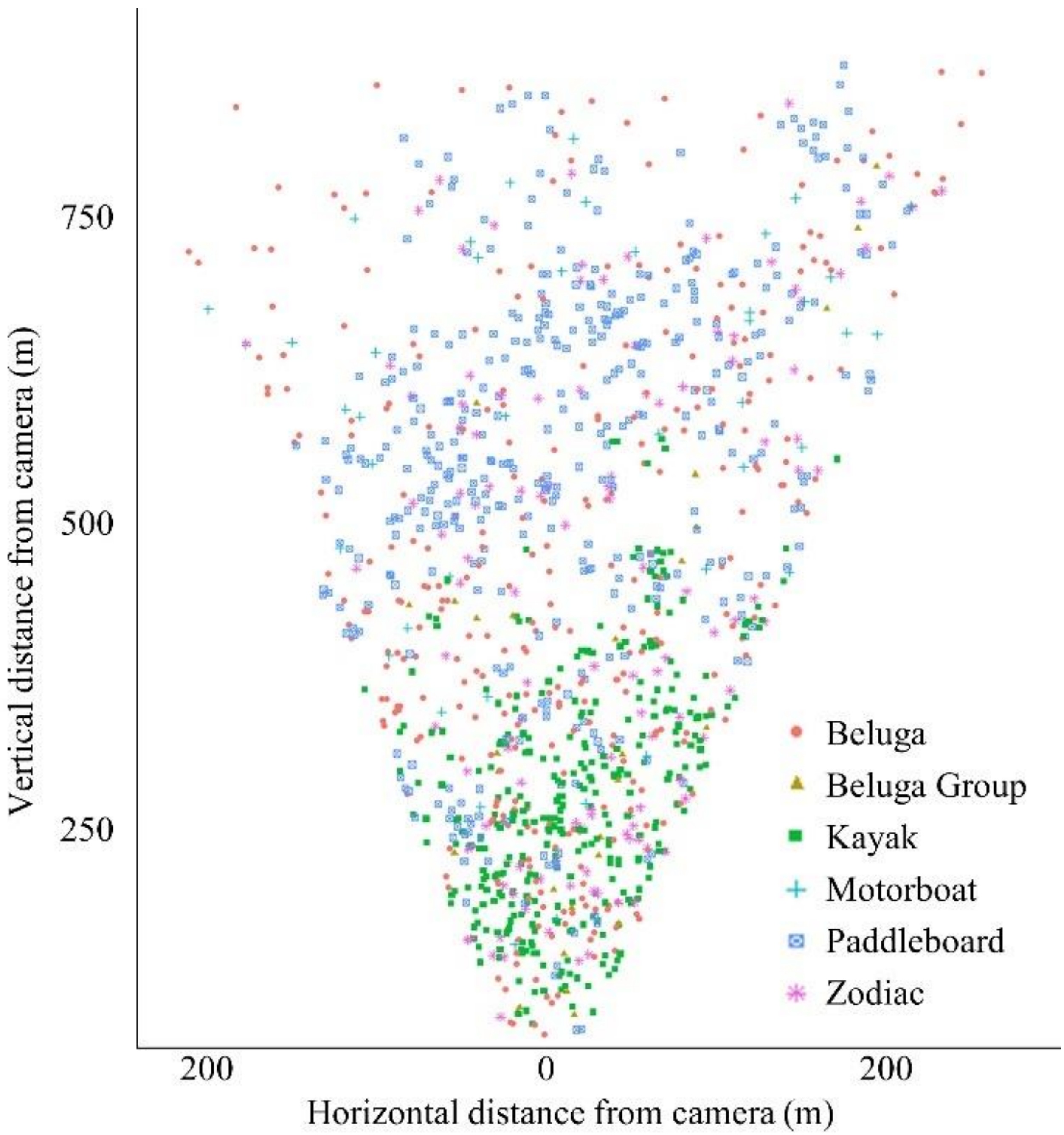


Figure 3. 10 Location of belugas, groups of belugas, and vessels with respect to camera location. Locations determined using equations outlined in the methods section of this paper.

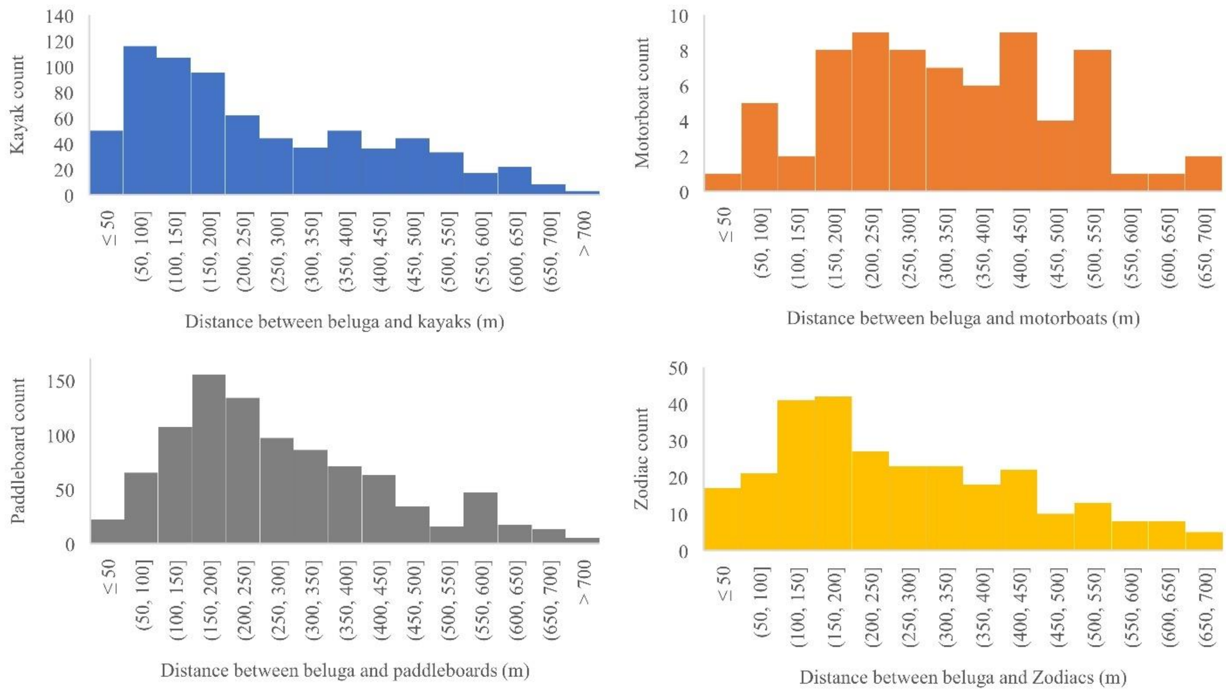


Figure 3. 11 Distribution of distances in meters between surfacing beluga and all kayaks (n = 724), motorboats (n = 71), paddleboards (n = 932), and Zodiacs (n = 278) captured in a photo.

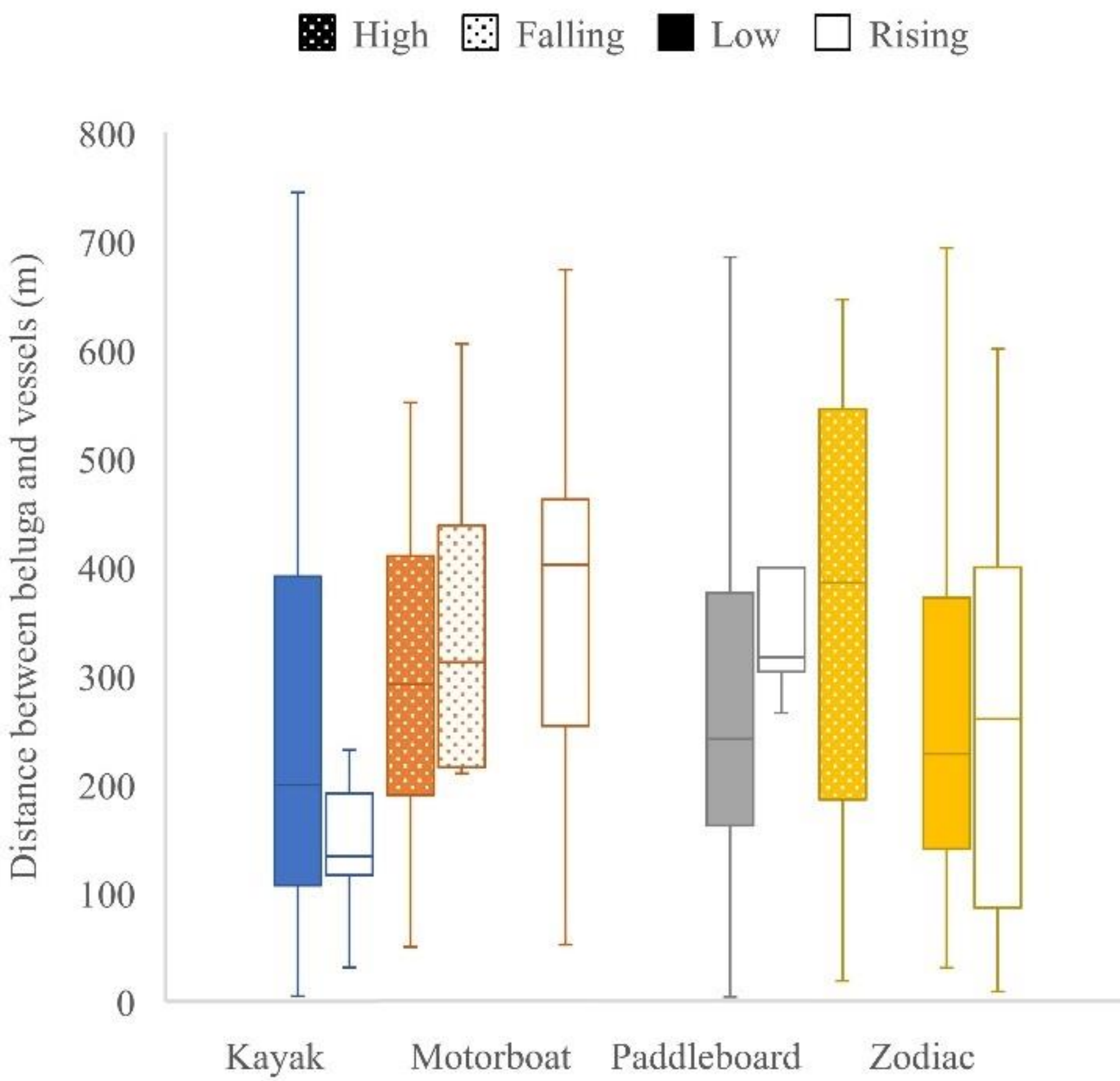


Figure 3. 12 Distance between surfacing beluga and vessels by vessel type and tide. Quartiles calculated using inclusive median shown at edges of the box, center line of the box and ends of the tails. Sample sizes by box as follows: kayaks at low tide (n=709), kayaks at rising tide (n=15), Motorboats at falling tide (n=7), motorboats at high tide (n=40), motorboats at rising tide (n=24), paddleboards at low tide (n=920), paddleboards at rising tide (n=12), Zodiacs at high tide (n=12), Zodiacs at low tide (n=254), Zodiacs at rising tide (n=12).

3.4.1 Kayaks

Kayaks were captured in photos during low tide and at the beginning of rising tide. Kayaks were present in the estuary in larger numbers as a part of tourist groups along with paddleboards and Zodiacs. The largest number of kayaks captured was 15 in one photo. The closest beluga to a kayak was 4.5 meters away. In 94 out of 100 iterations the distance between observed beluga and all kayaks was significantly less than the expected distances generated in a Monte Carlo Simulation showing attraction (Table 3.3).

Table 3. 2 Independence, attraction, and avoidance results from one-sided Wilcoxon Rank sum tests out of 100 iterations for beluga distance relationships to kayaks, motorboats, paddleboards, and Zodiacs.

	Independence	Attraction	Avoidance
Kayak	6	94	-
Motorboat	100	-	-
Paddleboard	-	-	100
Zodiac	100	-	-

3.4.2 Motorboats

Motorboats were captured in all but low tide photos. No more than one motorboat was present in a photo. Motorboats were found no closer than 49.6 m away from belugas. Independence was found between belugas and motorboats in all Monte Carlo simulation iterations (**Table 1**).

3.4.3 Paddleboards

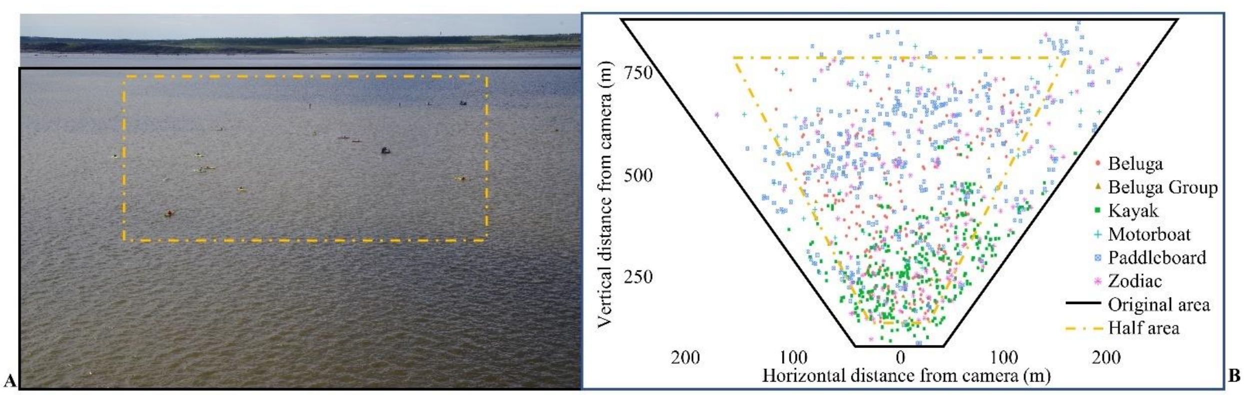
Paddleboards occupied the estuary during low and rising tide as part of larger tourist groups, with maximum number of 11 captured in one photo. Paddleboards were generally distributed near the center of the estuary between 500 and 800 meters from the camera (**Figure 9)** The closest beluga to a paddleboard was 3.6 meters away, which was the closest distance between a beluga and a vessel captured. In all 100 iterations of the Monte Carlo analysis the distance between observed belugas and paddleboards was significantly greater than expected indicating avoidance (**Table 1**).

3.4.4 Zodiacs

Zodiacs were captured in the estuary at all tides except falling. At low and rising tide, Zodiacs in the estuary were tour leaders there for supervision of kayaks and paddleboards. Of the 83 photos with Zodiacs and belugas, 9 only contained Zodiacs as the sole vessel. The closest beluga to a Zodiac was 8.5 meters. Independence was found between observed and expected distances between Zodiacs and belugas in 100 out of 100 iterations (**Table 1**).

3.4.5 Edge impacts

An edge impact would affect results from this analysis if there were belugas or boats just out of view of the photo. Because we are considering the distance relationships of belugas to boats, we can test for an edge impact by removing vessels from the ends of the image and complete the same analysis. Belugas in 50% of the photo area (does not change with tide) were removed from analysis by cropping the edges of the photos. Belugas within x from 1350 to 6010 and y of 750 to 3000 remained for analysis along with all vessels from the original photo dimensions (Figure 3.13). Results from 100 iterations of this analysis are shown in Table 3.3 which match Monte Carlo analysis conducted in the methods section of this paper.



Supplementary Figure 1. (A) Areas where belugas remained to test for edge impacts in yellow represented in the photo. **(B)** Areas where belugas remained to test for edge impacts in yellow and the distribution of these belugas and vessels with respect to the camera.

Figure 3. 13 (A) Areas where belugas remained to test for edge impacts in yellow represented in the photo. (B) Areas where belugas remained to rest for edge impacts in yellow and the distribution of these belugas and vessels with respect to the camera.

Table 3. 3 Independence, attraction, and avoidance results from one-sided Wilcoxon Rank sum tests out of 100 iterations for beluga distance relationships to kayaks, motorboats, paddleboards, and Zodiacs with removal of beluga from the edges to test for edge-impacts.

	Independence	Attraction	Avoidance
Kayak	-	100	-
Motorboat	100	-	-
Paddleboard	-	-	100
Zodiac	100	-	-

3.5 Discussion

This study finds that in response to all vessels, belugas in the Churchill River estuary are attracted to kayaks, avoid paddleboards, and are independent from motorboats and Zodiacs. To our knowledge, this is the first study finding attraction to kayaks by cetaceans using the measured distances between them. Our results support findings by Malcolm and Penner (2011) which suggest belugas show attraction to kayaks through interactive behavior. Malcolm and Penner (2011) used land and vessel-based observers to classify beluga behavior and estimate the distance between beluga and boats, finding the most common behavior of belugas in within 25 meters of vessels was interaction. While observations of interaction by Malcolm and Penner (2011) were consistent regardless of vessel type, we found independence relationships between beluga-vessel distance relationships to Zodiacs and motorboats. Differences in results are possibly related to data collection techniques, as Malcolm and Penner (2011) relied on visual observations of beluga behavior and estimation of distances, which can be biased through misclassification of observers.

The Churchill River estuary is a unique environment because of the attraction and independence belugas exhibit to whale-watching vessels. These responses by belugas can likely be attributed to population and location characteristics. Displays of attraction and interaction with kayaks may be related to the high sociality of the species (Malcolm & Penner, 2011; O’Corry-Crowe et al., 2020). Unlike offshore waters near other Arctic communities within the Hudson Bay, there are only few reports of belugas being hunted within the Churchill River estuary. Beluga hunting, which is traditional right for Inuit and Cree Peoples, has been observed to result in avoidance by beluga of boats historically within Churchill and in other communities around the Hudson Bay (Caron & Smith, 1990; Doniol-Valcroze et al., 2013; Idle, 1989; Malcolm & Penner, 2011; Tyrrell, 2007).

Compared to the St. Lawrence River beluga population, the attraction and independence behaviors Churchill beluga display to whale watching vessels are distinct. In the St. Lawrence River, belugas have been observed avoiding motorboats by increasing swimming speed, bunching into groups, changing travel direction, and increasing diving intervals (Blane & Jaakson, 1994; Lesage et al., 1999). Vessel avoidance displayed by these belugas could be a result of high traffic from ferries and shipping vessels in the estuary, which likely contributes to their status as Endangered (COSEWIC, 2014). Quantity, speed, approach distance, and regulation of tourist vessels have been shown to impact the behavioral response of beluga (Blane & Jaakson, 1994; Vera V. Krasnova et al., 2020). Current management of beluga ecotourism includes a 400 meter approach distance for belugas in the St. Lawrence estuary, as well as a 50 meter approach distance for belugas in the Seal and Churchill River estuaries (*Regulations Amending the Marine Mammal Regulations. SOR/2018-126*, 2018).

This is the first known study to find cetaceans located closer to kayaks than expected, showing attraction. In response to kayaks, whale behavior changes and horizontal avoidance have been recorded (Fandel et al., 2015; Jelinski et al., 2002; David Lusseau, 2003a, 2006; Noren et al., 2009; Sullivan & Torres, 2018; Timmel et al., 2008), while other studies have found no changes in certain cetacean behaviors (Heenehan et al., 2017; Steckenreuter et al., 2012). Williams et al. (2011) found that southern resident killer whales (*Orcinus orca*) reduced feeding and increased traveling behaviors when kayaks were present. It has been hypothesized that cetaceans avoid motorized boats due to their acoustic noise which can mask call communication, thus impacting communication or feeding (Christine Erbe, 2002; Holt et al., 2009; Lesage et al., 1999; Nowacek et al., 2007; Pirotta et al., 2015; Scarpaci et al., 2000). Avoidance exhibited by killer whales to kayaks indicates their presence can also be a disturbance factor (Williams et al., 2011). With minimal noise produced by kayaks, they are thought to result in avoidance by cetaceans through a ‘surprise’ disturbance, causing altered behaviors in whales (Gregory & Rowden, 2001; Sullivan & Torres, 2018).

Behavioral responses by whales to vessels can change over time. After a decade Burrunan dolphins (*Tursiops australis*) increased both avoidance (10.8 to 56.5%) and approach (3.3% to

10%) behaviors to vessels (Filby et al., 2014). Reduced behavioral response over time is generally classified as habituation, but could also be interpreted as reduced ability to respond due to decreased fitness (David Lusseau & Bejder, 2007). Decreased observations of belugas fleeing or diving to avoid tourist vessels over a 16 year period may be a evidence of habituation to vessel presence in the White Sea, Russia (Vera V. Krasnova et al., 2020). Whale-watching tourism with kayaks, motorboats and Zodiacs has been ongoing in the Churchill River estuary for decades (Malcolm & Penner, 2011). In 2015, paddleboards were added as a personal watercraft whale-watching option (http://www.sup-north.com/about). Beluga avoidance to paddleboards in the estuary may be because there has not been as many years for habituation. Longer term presence of paddleboards in the Churchill River estuary could change avoidance patterns.

This is the first paper to record interactions between paddleboards and belugas. When observing dolphin reactions to recreational activities including paddleboards, Fandel et al. (2015) recorded neutral responses 61.93% of the time. The closest beluga in our study was 4.6 meters away from a paddleboard. Paddleboards are less mobile than kayaks and more difficult to maneuver, which would limit the ability to approach beluga. One alternative explanation for avoidance to paddleboards found in the Churchill River estuary may be related to the large number of paddleboards found in close proximity to each other. Greater intensity of behavioral responses with increasing numbers of vessels has been observed in humpback whales (Amrein et al., 2020; Schuler et al., 2019), killer whales (Williams et al., 2009), Risso's dolphins (*Grampus griseus*) (Visser et al., 2011), Hawaiian spinner dolphins (*Stenella longirostris*) (Timmel et al., 2008), dusky dolphins (*Lagenorhynchus obscurus*) (Lundquist et al., 2013) and bottlenose dolphins (*Tursiops spp*.) (Rochelle Constantine et al., 2004; Pirotta et al., 2015; Steckenreuter et al., 2012; Stensland & Berggren, 2007). We found as many as 19 vessels in one image, which included Zodiacs, paddleboards, and kayaks (between 1 and 19 with a mean of 9.5 vessels). Paddleboards in the Churchill River estuary are often in clumped groups likely due to limited mobility. Large number of vessels occur because personal watercraft tour operators take advantage of the 3-hour low tide period when currents are calmer in the Churchill River estuary. However, kayaks are also found in larger groups which has not been shown in this research to effect beluga attraction. As large groups of vessels are often present in the Churchill River estuary during low tides, variation in beluga response with increasing numbers of vessels should be further investigated.

Ninety vessels (4.5% of distances between belugas and all vessels) were recorded within the 50 meter approach distance to beluga as defined by Marine Mammal Regulations in the Churchill River estuary (*Regulations Amending the Marine Mammal Regulations. SOR/2018-126*, 2018). There is evidence that increased proximity of vessels to whales may result in increased negative behavioral reactions (Currie et al., 2021; Schaffar et al., 2013; Steckenreuter et al., 2012). With decreasing distance to vessels, southern resident killer whales showed increases in respiration interval and path deviation as well as exhibiting more surface behaviors (Noren et al., 2009; Williams et al., 2009). Within 100 meters of vessels, humpback whales were more likely to exhibit avoidance behaviors (Stamation et al., 2010). In the White Sea, less behavioral changes were noted when vessels were further away from belugas (Vera V. Krasnova et al., 2020). The Churchill River estuary is a popular ecotourism and research destination, with projected increases in visitors over time for the unique opportunities (Malcolm & Penner, 2011). With this in mind, impacts of proximity and quantity of vessels in the estuary are important factors to consider with respect to beluga response as well as population health.

Results from this paper show that vessel type results in differing responses by beluga whales in the Churchill River estuary. This is different from conclusions drawn by Malcolm and Penner (2011) who noted that belugas appear interactive to tourist vessels regardless of type. Variation in responses to different vessel types have been recorded in gray whales (*Eschrichtius robustus*) in Oregon, as they were less likely to continue searching for food within 250 meters of motorized boats than kayaks, with the opposite for foraging (Sullivan & Torres, 2018). Southern resident killer whales demonstrate alternative responses to whale-watching depending on vessel type, including horizontal avoidance to kayaks, and differences in display of surface active behaviors at varying approach distances by vessel type (Noren et al., 2009; Williams et al., 2009). Bottlenose dolphins (*Tursiops truncates*) in West Whales exhibited attraction, avoidance and independence in different proportions depending on vessel type (Kayak, speeding boat, fishing boat, sailing boat) (Gregory & Rowden, 2001).

Determining the population level impact of whale watching is complicated as the relationship between short-term behavioral responses and fitness is unknown (New et al., 2015). We documented avoidance and attraction by beluga with respect to kayaks and paddleboards. Avoidance could be an indicator of stress (New et al., 2015; Orams, 2004), and is often described in cetacean research as a similar response to predator avoidance (Frid & Dill, 2002; David

Lusseau, 2003b; Williams et al., 2002). Higher respiration rate in addition to other behaviors that accompany avoidance could negatively impact whale energy reserves (Christiansen et al., 2014). By avoiding paddleboards, belugas may also lose opportunities to access habitat benefits hypothesized for estuary occupation, including access to prey. Reduced feeding is often recorded as a cetacean response to vessels (Arcangeli & Crosti, 2009; Christiansen et al., 2013b; Dans et al., 2012; David Lusseau et al., 2009; Pirotta et al., 2015; Steckenreuter et al., 2012; Stockin et al., 2008; Williams et al., 2006b, 2011), which can reduce energy intake, especially if vessels are occupying areas that are necessary for feeding (Senigaglia et al., 2016).

3.5.1 Conclusion

Using a time-lapse camera system, we were able to capture 2,261 surfacing belugas in 16 days on the Churchill River estuary. The use of trigonometric equations along with georeferencing points taken allowed for measurement of the distance between surfacing beluga and vessels. We found that belugas were located closer to kayaks, further from paddleboards, and no closer or further from Zodiacs and motorboats than would be expected indicating attraction to kayaks, avoidance to paddleboards, and independence from motorboats and Zodiacs.

Issues of whale conservation and management require clear defensible scientific data upon which policies and procedures can be developed. Climate variability and change and other pressures on Arctic flora and fauna can also affect relationships measured here. We suggest ongoing monitoring of whale boat interactions to support species management in this unique sub-Arctic estuary. The beluga tourism industry in Churchill, Manitoba has many stakeholders. As such, it is important to consider the impact of this industry on the health of the beluga population, the local economy, and the tourists themselves. The ecotourism and whale-watching industry is an important source of jobs and income in Churchill, Manitoba. The estimated economic impact of beluga tourism was $1,344,052 CAD for Northern Manitoba in 2014, with 60 direct full and part time jobs for Manitobans (The Churchill Beluga Whale Tour Operators Association et al., 2015). Ecotourism can be a tool to educate participants about whale conservation (Cárdenas et al., 2021; García-Cegarra & Pacheco, 2017), and the uniqueness of this sub-Arctic environment could increase awareness on how climate change affects flagship species. Tourism vessel impacts on beluga in the Churchill River estuary will be an important factor for decisions with respect to the establishment of a National Marine Protected Area. We also recommend ongoing monitoring of these relationship to ascertain the veracity and potential change in these relationships through time.

4 Chapter 4: Conclusion

4.1 Summary

Chapter 1:

In this chapter, the status of the Western Hudson Bay beluga whale population was reviewed with respect to environmental characteristics of summer estuary habitat and anthropogenic activities which may impact population health. Despite its status as the largest known beluga population, research gaps included areas important for beluga habitat use, environmental conditions that drive beluga distribution, and the impact of shipping and tourism vessel traffic.

Chapter 2:

Critical beluga habitat areas were investigated using beluga locations identified in aerial photos and environmental variables collected from remotely sensed data. This is the first known study to use remotely sensed concentration of total suspended sediment and colored dissolved organic matter to evaluate beluga habitat distribution. Additionally, river plume boundaries for the Seal, Knife and Churchill Rivers were compiled for beluga habitat modeling. Discrete habitat units in the western Hudson Bay were first identified through classification using environmental variables, which revealed that the Knife River area should also be considered as a high occupation area for beluga. The inclusion of CDOM or TSS as well as distance to the river plume or river mouth were included in models describing beluga distribution for each area. These environmental characteristics can be tied to nutrient and light availability for primary production, connecting beluga habitat selection with prey distribution in summer estuary habitat.

Chapter 3:

Whale-watching is a popular form of ecotourism, which can result in negative impacts to the observed species, including avoidance and behavior changes. Research has shown that the vessel type, quantity of vessels, and vessel maneuvering, as well as the species and population of cetacean observed, result in differing responses by cetaceans to whale-watching. For this reason, it is important to assess for impacts of whale-watching industries on individual populations. The tourism industry in Churchill, Manitoba, Canada is a unique example of cetacean response to whale-watching vessels, as occurrences of interaction to tourist boats by beluga are observed. In this chapter, distance measurements were used to determine that beluga respond to whale-watching vessels in the Churchill River estuary by showing attraction to kayaks, avoidance to paddleboards and independence to motorized vessels. While these results are important for local management decisions, they also give an example of a more unique case of attraction and independence to whale-watching. This research also demonstrates the use of a time-lapse camera system to obtain useful information on cetacean populations through image captures of surfacing beluga. These methods can be replicated to investigate habitat use of marine mammals and their response to anthropogenic activities.

4.2 Limitations and future directions

4.2.1 Remote sensing habitat investigation

The 2018 aerial photographic surveys occurred at different tide levels for each of the estuaries, with several days in between each survey (**figure #**). The tidal amplitude in the western Hudson Bay is large, with a tidal amplitude as great as 5 m recorded at Port Nelson in the Nelson River estuary (Wang et al., 2012). Beluga estuary distribution is connected to tide, following high tide upriver and low tide downriver and away from the shore (Caron & Smith, 1990; Doan & Douglas, 1953; Hansen, 1988; V V Krasnova et al., 2012). Aerial surveys of the Churchill River found congregations of beluga in the southern end of the estuary during high tide and fewer beluga present in the estuary during low tide (Idle, 1989). Beluga were observed moving in an out of the Nelson river estuary with the tide, with higher use by belugas during high tide (R. Baker, 1989; A. J. Smith et al., 2017). Availability of shallow intertidal areas are impacted by tide, with large areas exposed along the western Hudson Bay shoreline at low tide. Sea level in the Cook Inlet, Alaska estuary was associated with beluga movements between shallow intertidal areas with rising tide (Ezer et al., 2008). Differences in tide likely impacted beluga distribution in each of the models and habitat areas.

Environmental characteristics of estuary habitat areas were compiled based on available satellite data. This data is limited by the resolution, sampling dates, and cloud cover. Ideally habitat data would have been collected from the date and the time of each aerial survey to best collect the habitat characteristics associated with each beluga location. MODIS compiled surface chlorophyll a concentration and sea surface temperature is available at 1km resolution. For chlorophyll a, there were multiple missing pixels, which in this analysis were estimated using kriging. Sentinel 2 data, while at a higher resolution of 10 m, was not available from survey dates. Though Sentinel 2 has a 2-3 day revisit period, clouds fully or partially covered the estuary areas during many of the dates (https://sentinel.esa.int/web/sentinel/missions/sentinel-2). For this reason, the concentration of CDOM, concentration of TSS and river plume boundaries were generated using the 2 or 4 available images for each location. These factors may contribute to inaccuracies in the environmental data, however, estimates for each environmental factor still contributed to meaningful models for each habitat area.

Advances in remote sensing of oceanographic characteristics has the high potential to contribute to the study of marine mammals, which are complicated by their long life, migratory patterns, remote habitat, and limited time spent at the water's surface. Measurements of chlorophyll a, TSS and CDOM concentration are not a perfect representation of light availability, nutrient availability, and resulting phytoplankton biomass and primary productivity. Other factors such as stratification, weather, mixing of water layers from winds and currents, tide, salinity, and how primary productivity equates to secondary production and overall, availably of prey resources impacts overall distribution and production in estuaries (Cloern 1987, Cloern et al. 2014, Azhikodan and Yokoyama 2016, McSweeney et al. 2017). They can be however used to represent these concepts in an area where prey distribution and other habitat variables are not known completely, as is the case in the western Hudson Bay (Ferland et al. 2011, Sigman and Hain 2012). Our research was limited by the availability and resolution of cloud free satellite imagery on the dates of aerial surveys. Despite this TSS or CDOM were important in all models and show potential for descriptions of beluga habitat use in the future. Belugas and narwhals can be identified and located using satellite imagery (Charry et al. 2021). By sampling multispectral bands while collecting images, habitat data could be collected simultaneously with beluga location.

4.2.2 Time-lapse camera systems for cetacean monitoring

This is the first known research to investigate for horizontal attraction, avoidance, or independence by cetaceans to vessels using oblique images. Time-lapse photos have been used previously in marine biology to identify sources of acoustic noise (Merchant et al., 2014), detect southern right whales (*Eubalaena australis*) (Rayment et al., 2018), and locate Indo-pacific bottlenose dolphins (*Tursiops aduncus*) within a channel (Paiva et al., 2015). Distance calculations determined for this paper relied on previous research on oblique image measurements (Havens & Sharp, 2015; Höhle, 2008; Whitehead, Moorman, & Wainstein, 2010). Identifiable landmarks in images have been used determine the location of dolphins within a channel, which was tested through the use of georeferencing points (Paiva et al., 2015). Pavia et al. (2015) used onshore reference points and a false horizon to locate dolphin captures from photos of Freemantle Harbour, Australia within a range of 10- 347 meters from a camera system. Our research made use of georeferencing points to calibrate and test accuracy of measurements, which supplemented the need for known locations in images. This system has proven to be effective in identifying beluga within 82.3 and 925.8 meters from the camera at low tide. Through testing of the georeferencing points we found that error between calculated distances from the camera to the seven points ranged from 1.7 meters to 10.0 meters with a mean of 6.6 meters. The larger range and increased accuracy of our measurements can likely be attributed to camera position higher above the estuary, higher camera resolution (36.4 megapixels vs 10 megapixels), and alternative measurement techniques for determining cetacean location (Paiva et al., 2015).

The methodology employed for this project was successful for the following reasons that should be considered when using oblique camera monitoring. First, the study species of beluga whales frequently occurred in the area captured by the camera. An estimated 3,136 belugas were found in the Churchill River estuary and surrounding areas at the time of the most recent photographic survey (Matthews et al., 2017). This contributed to the high capture of surfacing beluga in 47% of photos. Second, the Port of Churchill gallery was an optimal spot for camera set up, as the height as well as location allowed for photo capture of a large section of the estuary frequented by belugas and tourists. Third, the camera system was accessible allowing for frequent checks to insure proper operation and maintenance.

Distance measurements in whale watching studies are determined using estimation (Stamation et al., 2010; Steckenreuter et al., 2012), laser range finders, (Baird & Burkhart, 2000; Filby et al., 2014; Noren et al., 2009) and theodolites (Bejder et al., 1999; Jelinski et al., 2002; Kruse, 1991; Lundquist et al., 2013; Santos-Carvallo et al., 2021; Schaffar et al., 2013; Scheidat et al., 2004; Schuler et al., 2019; Sullivan & Torres, 2018; Timmel et al., 2008; Williams et al., 2002, 2009). In investigating compliance to an approach distance in Hawaii, Baird and Burkhart (2000) reported underestimation of distances between Humpback whales and vessels by boat captains compared to laser range finder measurements (Baird & Burkhart, 2000). Measured distances from a time-lapse camera system improve on estimated distances by reducing observer bias. Compared to laser range finders, and theodolites the error associated with measurements in this study is less accurate (RMSE of 4 m). The camera system is advantageous in comparison to laser and theodolite measurements by not requiring manual opportunistic measurements. Additionally, a vessel is not needed to collect data, which could bias results on whale watching studies through additional disturbance (Magalhães et al., 2002; Scheidat et al., 2004). Without technical system errors, time-lapse cameras would greatly reduce data processing time. For this project the visual inspection of images to identify beluga and vessel sightings was the most time-consuming aspect. However, automatic detection systems are advancing and have the potential to correctly classify images. One detection system has been developed from imagery of vessels and belugas in the in Churchill estuary (Harasyn et al, in review). The greatest advantage of the time lapse system in this project is the amount of data that can be captured systematically. In this paper it allowed us to compile an expected distribution using true beluga locations. Potential future studies utilizing oblique camera systems include investigating direction of travel, age class, grouping patterns, and migratory timing for beluga in the Churchill River estuary.

4.3 Conclusion

The summer estuary habitat for WHB belugas is changing due to increased water temperatures and increased anthropogenic activities. WHB belugas are an important natural resource in Manitoba that should be managed to ensure long-term success. Protection proposed for the WHB population in Manitoba has included the establishment of a National Marine Protected Area with various zones and regulations (Labun & Debicki, 2018; Manitoba western Hudson Bay ad hoc beluga habitat sustainability plan committee, 2016). The research completed in this thesis, including evaluation of the environmental features that contribute to optimal beluga habitat and investigation of the relationship between tourism vessels and belugas, should be used to inform management decisions. A total of 3,593 beluga were identified in 4,629 aerial survey and 2,303 oblique time-lapse images. Habitat analysis of aerial survey photos from summer 2018 revealed connections between beluga distribution and river influenced and water quality environmental variables. These relationships show a strong relationship between beluga summer habitat use, rivers, and prey. Time-lapse images from August 2020 captured optimal habitat in the Churchill River estuary as determined by predictive maps in Chapter Two. We found that belugas were located closer to kayaks, further from paddleboards, and no closer or further from Zodiacs and motorboats than would be expected indicating attraction to kayaks, avoidance to paddleboards, and independence from motorboats and Zodiacs. The new methods developed and utilized in this research show high potential for further investigations into marine mammal response to anthropogenic activities, and habitat modeling of belugas and other cetaceans with respect to remote sensing derived environmental variables.

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