Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2017/061

Central and Arctic Region

Estimated abundance of the Western Hudson Bay beluga stock from the 2015 visual and photographic aerial survey

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October 2017

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Matthews, C.J.D., Watt, C.A., Asselin, N.C., Dunn, J.B., Young, B.G., Montsion, L.M., Westdal, K.H., Hall, P.A., Orr, J.R., Ferguson, S.H., and Marcoux, M. 2017. Estimated abundance of the Western Hudson Bay beluga stock from the 2015 visual and photographic aerial survey. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/061. v + 20 p.

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ABSTRACT

Aerial visual and photographic surveys of summering Western Hudson Bay (WHB) beluga (*Delphinapterus leucas*) were conducted in August 2015 to update the previous stock abundance estimate from 2004. The survey area comprised five strata (three visual and two photographic) encompassing high use areas around three river estuaries where recurring aggregations of WHB beluga are found during the summer months. The photographic surveys completely covered high density aggregations in the Churchill River and near the mouth of the Seal River. Poor weather conditions prevented replicated surveys of all but the Churchill River photographic stratum. Near-surface abundance estimates for each stratum were adjusted for availability bias using dive data collected from eight satellite-tagged WHB belugas during the same period as the aerial survey. Belugas in rivers spent 58.3 ± 3.7 % of their time within the 0–2 m depth bin, resulting in a correction factor of 1.71 ± 0.11 for murky water, while belugas in coastal areas spent 80.9 ± 3.0 % of their time within the 0–5 m depth bin, resulting in a correction factor of 1.24 ± 0.05 for clear water. Summed corrected stratum abundance estimates provided a total stock abundance estimate of 54,473 (CV = 0.098, 95 %; CI = 44,988–65,957).

Estimation de l'abondance du stock de bélugas de l'ouest de la baie d'Hudson à partir des relevés visuels et photographiques aériens de 2015

RÉSUMÉ

Des relevés visuels et photographiques aériens des bélugas estivants de l'ouest de la baie d'Hudson (*Delphinapterus leucas*) ont été effectués en août 2015 afin de mettre à jour l'estimation de l'abondance du stock précédent, qui datait de 2004. La zone du relevé comprenait cinq strates (dont trois visuelles et deux photographiques) englobant des zones très fréquentées situées à proximité de trois estuaires de rivières où des regroupements de bélugas de l'ouest de la baie d'Hudson se retrouvent pendant l'été. Les relevés photographiques couvraient la totalité du regroupement à forte densité dans la rivière Churchill et près de l'embouchure de la rivière Seal. Il a été impossible d'effectuer des relevés répétés en raison de conditions météorologiques défavorables, sauf en ce qui concerne la strate photographique dans la rivière Churchill. Les estimations d'abondance de la strate près de la surface ont été ajustées en fonction du biais de disponibilité au moyen de données sur les plongées recueillies auprès de huit bélugas de l'ouest de la baie d'Hudson portant des étiquettes satellites pendant la même période que les relevés aériens. Les bélugas se trouvant dans les rivières passaient 58,3 ± 3,7 % de leur temps dans une tranche de 0 à 2 m de profondeur, entraînant un facteur de correction de 1,71 ± 0,11 en raison de l'eau trouble, alors que les bélugas se trouvant dans les zones côtières passaient 80,9 ± 3,0 % de leur temps dans une tranche de 0 à 5 m de profondeur, entraînant un facteur de correction de 1,24 ± 0,05 en raison de l'eau limpide. La somme des estimations corrigées de l'abondance par strate a permis d'établir une estimation totale de l'abondance du stock de 54,473 (coefficient de variation = 0,098, 95 %; intervalle de confiance = 44,988 – 65,957).

INTRODUCTION

Western Hudson Bay (WHB) belugas (*Delphinapterus leucas*) form one of two stocks that migrate seasonally through Hudson Strait to recurring summering areas in Hudson Bay (Turgeon et al. 2012). From mid-June to September, WHB belugas are distributed along the west coast of Hudson Bay from Ontario to Nunavut. During summer, large aggregations predictably occur within and near the Churchill, Seal, and Nelson River estuaries and adjacent coastal areas. WHB belugas can be differentiated genetically from the neighboring Eastern Hudson Bay (EHB) and James Bay (JB) stocks, and from more distant beluga populations such as those in the St. Lawrence River and Beaufort Sea (de March and Postma 2003, Doniol-Valcroze et al. 2016).

The WHB beluga stock is harvested by Nunavut and Nunavik Inuit. The average annual harvest of WHB belugas was approximately 300 animals from 2000–2015. Additionally, WHB belugas are subject to direct and indirect impacts of sea ice reductions in Hudson Bay (COSEWIC 2004). These include altered food webs, increased shipping and other industrial activity, and potential increases in predation by killer whales, whose presence in Hudson Bay has increased over recent decades (Higdon and Ferguson 2009).

An aerial visual and photographic survey of the WHB beluga stock in 2004 produced an abundance estimate of 57,300 individuals (Richard 2005; see publication for additional abundance estimates incorporating different combinations of survey strata). Uncorrected surface counts from the 2004 aerial survey were similar to those from a comparable survey conducted in 1987 (Richard et al. 1990). Based on this, Richard (2005) concluded that WHB beluga stock abundance had not changed significantly during the interim period.

This report provides an updated WHB beluga abundance estimate based on aerial visual and photographic surveys conducted across the summer distribution of WHB belugas during August 2015. We included strata based largely on the 2004 survey design (Richard 2005), and incorporated high-use areas defined from movements of satellite-tagged WHB belugas (Smith et al. 2017, DFO unpublished data). We also used concurrent dive data from eight satellite-tagged WHB belugas to estimate availability bias (whales not observed at the surface because they were submerged).

METHODS

SURVEY AREA

Survey strata and effort were based largely on the most recently completed survey of the WHB beluga stock (Richard 2005). Data from belugas equipped with satellite-linked transmitters in the Nelson and Seal River estuaries (Smith et al. 2017, DFO unpublished data) were used to ensure the boundaries of high density strata encompassed high-use areas. The planned survey area extended from northern Hudson Bay to western Hudson Bay along the coasts of Manitoba and Ontario, and was divided into several strata that were assigned varying degrees of survey effort according to beluga density (Figure 1). Near-shore strata, comprising the Churchill River, the Seal River, and the Nelson River, included the Churchill High Density and Nelson River strata, which were surveyed visually using parallel transect lines spaced 12.5 and 18.5 km apart. Complete coverage photographic surveys were conducted of the Churchill River estuary (Churchill River Photographic stratum) and the mouth of the Seal River (Seal River Photographic stratum; Figure 1). The West Coast Low Density stratum was located farther offshore, and was surveyed visually with reduced effort (fewer transects in zigzag or saw-tooth pattern; Figure 1) based on tagging data and previous surveys indicating lower WHB beluga density offshore. The survey originally included the Eastern Low Density stratum extending from the eastern boundary of the Nelson River Stratum along the coast of northern Ontario to James Bay (Richard 2005), as well as a full survey of narwhals and belugas in northern Hudson Bay (Figure 1). However, poor weather conditions forced cancellation of these strata to focus on high priority areas.

VISUAL SURVEY

Surveys were flown in a DeHavilland Twin Otter (DH-6) fitted with four bubble windows and an optical glass-covered camera hatch at the rear underbelly of the plane. A Global Positioning System (GPS) unit logged the position, altitude, speed, and heading of the aircraft each second. Surveys were initially flown at a target ground speed of 100 knots (185 km/h), and target altitudes of 1,000 ft (305 m) for visual surveys and 2,000 ft (610 m) for photographic surveys. After the second day of flying, the target ground speed was adjusted to 110 knots (204 km/h) after the pilots indicated that it would facilitate maintenance of a level pitch.

Four observers, two on each side of the aircraft, were seated at bubble windows. Observers were instructed to focus on the area closest to the track line and to use their peripheral vision for sightings farther afield. Beluga sightings were recorded using a Sony PCM-D50 audio recorder, including the number of individuals in each group (defined as animals within one body length of each other and behaving cohesively, i.e., travelling together). The perpendicular declination angle to the center of each group was measured using a clinometer when it was abeam to the observer. When time permitted, observers provided additional observation details, such as the direction of travel, presence of calves, and behaviour. The two primary observers also described ice concentrations (in tenths), sea state (Beaufort scale), fog (% of field of view), glare (% of field of view), and cloud cover (percentage) at the start of each transect and when conditions changed during the survey.

The area directly below the aircraft was photographed continuously throughout each visual survey using the same photographic method described below. However, only photographs from the high density photographic strata were used to estimate abundance.

PHOTOGRAPHIC SURVEY

Complete coverage of the two photographic strata was achieved using a Nikon D810 camera fitted with a 25 mm lens. The camera was mounted at the rear of the aircraft and directed straight down with the longest side perpendicular to the track line. The camera was connected to a GPS unit to geo-reference photographs, and to a laptop computer to control exposure settings and photo interval. At an altitude of 2,000 ft (610 m), the 25 mm lens captured a ground area of approximately 875 m x 585 m. The photograph interval was set to maintain an overlap of 20 to 40 % between consecutive photos, and with a transect spacing of 600 m, the lateral overlap between photos from adjacent transects was approximately 30 %.

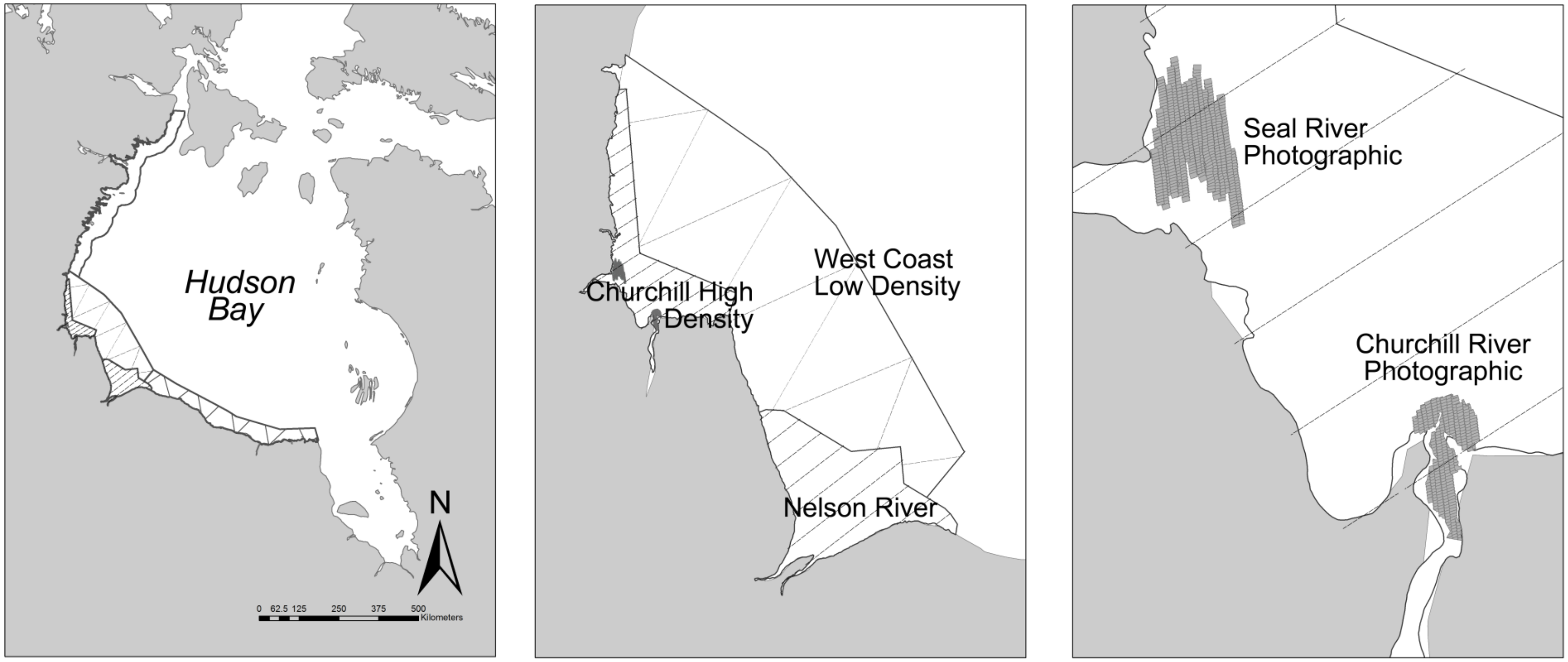

Figure 1. Survey location within Hudson Bay (left panel), completed visual survey strata with transect lines (middle panel), and completed full coverage photographic surveys (right panel).

DATA ANALYSIS

Visual Survey

Visual line-transect survey data were analysed using conventional distance sampling (CDS; Buckland et al. 2001) using Distance 6.2 software (Thomas et al. 2010). Briefly, CDS models the probability of detection as a function of observed distances from a line (or point) and estimates the effective strip half width (ESHW; see Buckland et al. 2001) to estimate density as:

$$\hat{D} = \frac{n \cdot \hat{E}(s)}{2 * L * ESHW}$$

with an associated variance of:

$$var(\hat{D}) = \hat{D}^2 \times \left\{ \frac{var(n)}{(n)^2} + \frac{var(ESHW)}{ESHW^2} + \frac{var(\hat{E}(s))}{(\hat{E}(s))^2} \right\}$$

where n is the number of detected groups, $\hat{E}(s)$ is the expected group size, and L is the sum of all transect lengths making up the survey (Buckland et al. 2001). Abundance is then estimated as:

$$\hat{N} = \hat{D} * A$$

where A is the area of the survey stratum.

Distance analysis was performed on observations from the three visual line-transect survey strata. Although surveys were conducted by paired observers on both sides of the aircraft, only observations made by the two front observers were analysed. The two rear positions were rotated throughout the survey by four observers with varying degrees of experience, whereas the two front positions were occupied by the same experienced observers throughout. This prevented estimation of perception bias, which incorporates observations from paired reviewers to assess the percentage of missed observations (Buckland et al. 2004; see Discussion).

A global detection function was calculated using combined observation data from all strata, which were all surveyed from the same platform by the same observers under similar conditions. Perpendicular distances were unavailable for approximately 10 % of beluga observations, so these data were excluded prior to model fitting for estimating detection probability and effective strip width (but were included for final density and abundance estimates). Fits of candidate key functions available in Distance 6.2 (Half-normal and Hazard-rate) in various combinations with candidate series expansions (Cosine, Simple polynomial, and Hermite polynomial) to ungrouped perpendicular distances were first assessed by Akaike information criterion (AIC) values. Conventional distance sampling assumes detection of all objects on the transect line (i.e., zero distance), which is not the case with aerial surveys since the area immediately under the aircraft may be obscured to observers. Sightings at extreme distances can also affect model fit and subsequent density and abundance estimates (Buckland et al. 2001). We therefore examined histograms and goodness of fit of the candidate models to test a range of left-truncation distances (50, 100, 150, and 200 m) and right-truncation distances where obvious gaps in the distribution of perpendicular distances occurred (800, 900, 1,000, 1,100, and 1,200 m). The impact of truncation on model fit was judged from p values of C^2 and W^2 statistics (J-F. Gosselin, DFO, pers. comm.).

After model selection and determination of appropriate left and right truncation distances, we assessed whether inclusion of the covariates “observer”, “Beaufort sea state”, “cloud cover”, and “glare” improved model fit (the covariates “ice cover” and “fog” were 0 throughout all surveys). Briefly, the best-fit model was re-fit using the MCDS engine in Distance 6.2, with each covariate included in a separate analysis (Marques and Buckland 2003). Since addition of no one covariate produced a lower AIC than the model including observation data alone (see 'Results'), MCDS was not pursued further.

The probability of detection (p) and its standard error (SE) from the best-fit model were used as multipliers in a final analysis incorporating all observations with both recorded and missing perpendicular distances. This analysis employed a uniform detection model with no adjustment term to estimate density and abundance by stratum, with density estimates divided by the probability of detection. Observations with missing perpendicular distances were assumed to have occurred within the truncated range (Doniol-Valcroze et al. 2015). To ensure estimated average group size was not biased with respect to perpendicular distance (e.g., if larger groups are more easily detected at greater distances from the track line), the natural logarithm of group size was regressed against the detection function value [g(x)], and mean group size was used in density estimates when *p* for the regression was > 0.15 (which was the case for all surveys).

Photographic Survey

Photos were examined on a 24-inch high resolution monitor, and manually adjusted for contrast and brightness as required using Adobe Photoshop. Belugas were counted and their locations were marked on georeferenced photos using ArcMap 10.1. Two experienced readers were familiarized with the size and shape of beluga whales using images from previous surveys. One reader counted all photos from two of the Churchill River photographic surveys (12 August afternoon and 19 August; see Table 1), while counts by both readers were combined for the Seal River photographic survey. In addition to counting belugas, the photo readers also visually estimated the portion of each photograph with sun glare. One reader repeated beluga counts and estimates of sun glare and murkiness for 118 photos after a period of several months had passed.

In each stratum, beluga density was determined by dividing the total near-surface count by the total water area (excluding sun glare, which masked beluga presence) across all photographs. Each photo was projected onto a high-resolution contour map of the coast. The surface area covered by each photograph was calculated as:

$$A_{photo} = \text{length} * \text{width}$$

where length = altitude/F_s*L_s and width = altitude/F_s*W_s, and F_s is the focal length of the camera sensor (25 mm), L_s is the length of the camera sensor (35.9 mm) and W_s is the width of the camera sensor (24 mm).

The portion of land was cropped from each photo:

$$A_{water} = A_{photo} - A_{land}$$

and then the proportion of water covered by sun glare (G) was subtracted from the water area:

$$A_{noglare} = A_{water} * (1 - G)$$

Stratum abundance was calculated by multiplying beluga density by the area of the polygon created by merging all photos, with land area subtracted. All analyses were conducted in the statistical software R (R Core Team 2014) using the packages raster (Hijmans 2015), sp (Pebesma and Bivand 2005), rgdal (Bivand et al. 2015), shapefiles (Stabler 2013), maptools (Bivand and Lewin-Koh 2015), rgeos (Bivand and Rundel 2014), mapproj (McIlroy 2014), and plyr (Wickham 2011).

Table 1. Summary of flights during the August 2015 aerial survey of beluga whales in western Hudson Bay. Visual surveys were conducted of the Churchill High Density, Nelson River, and West Coast Low Density strata, while Churchill and Seal Rivers were full-coverage photographic surveys.

Date	Start Time	End Time	Flight Length	Flight Description
06-Aug	10:08	14:29	04:21	Churchill High Density transects 1 to 10, Seal River photographic partial
12-Aug	10:25	16:10	05:45	Churchill River photographic, Churchill High Density transects 9 to 14, Seal River photographic
12-Aug	17:15	18:45	01:30	Churchill River photographic survey
13-Aug	11:30	14:27	02:57	Nelson River transects 6 to 9
16-Aug	09:43	13:34	03:51	West Coast Low Density transects 1 to 5
16-Aug	14:18	18:12	03:54	West Coast Low Density transects 6 to 10
17-Aug	09:37	15:03	05:26	Nelson River transects 1 to 9
18-Aug	10:00	12:00	02:00	Churchill High Density transects 1 to 3
19-Aug	09:23	13:49	04:26	Churchill High Density transects 12 to 15, Churchill River Photographic, and partial Photographic of Seal River

AVAILABILITY BIAS

To estimate marine mammal stock or population abundance, surface abundance estimates determined from aerial visual and photographic surveys must account for availability bias (i.e., the proportion of animals that occur at depths not visible to observers; Marsh and Sinclair 1989). Adult and juvenile beluga whales are visible at depths up to 5 and 2 m in clear water, respectively (Richard et al. 1994), while previous studies have assumed that belugas cannot be seen at depths greater than 2 m in murky water (Richard 2013). We used dive and location data from satellite tagged WHB beluga whales to calculate instantaneous availability bias correction factors for both visual and photographic surveys based on water clarity.

Tag deployment

Satellite linked time depth recorder tags (SPLASH tags, Wildlife Computers) were deployed on eight beluga whales (three females and five males) at Mosquito Point (56°68′ N, 94°19′ W), near Churchill, Manitoba, in July 2015 (Table 2). Methods for beluga capture and tagging have been published previously (Orr et al. 2001). Briefly, belugas were captured by encircling them with a 50 m net spooled out from a fast moving boat. Captured whales were held between two inflatable boats for instrumentation with a satellite-linked transmitter. Two to three 10 mm nylon pins were secured through the dorsal ridge and the tag was anchored to the pins with high-grade stainless steel cables looped around specially designed washers. This process was approved by the Freshwater Institute Animal Care Committee (FWI-ACC-2015-018).

Table 2. Deployment date, sex, approximate length, and number of 6-hour blocks collected in August during the day for beluga whales deployed with satellite-linked transmitters in 2015 Churchill River estuary. n = number of 6-h blocks during the day in August.

Tagging Location	***Deployment Date***	***Sex***	***Tag Number***	***Length (cm)***	***n***
Mosquito Point	*07-08-2015*	*F*	*128160*	*294*	*60*
Mosquito Point	*07-10-2007*	*F*	*128158*	*332*	*62*
Mosquito Point	*07-10-2007*	*M*	*128161*	*320*	*54*
Mosquito Point	*07-10-2008*	*F*	*128162*	*290*	*62*
Mosquito Point	*07-11-2008*	*M*	*128165*	*378*	*62*
Mosquito Point	*07-12-2008*	*M*	*128157*	*340*	*62*
Mosquito Point	*07-14-2008*	*M*	*128164*	*347*	*56*
Mosquito Point	*07-14-2006*	*M*	*128155*	*358*	*62*

Telemetry data analysis

Satellite tags were programmed to transmit hourly, but dive data were summarized into four 6-hour histograms starting at 00:00, 6:00, 12:00 and 18:00 local time. Since surveys were conducted during the hours of 9:00 and 18:00, we restricted our analysis to all available daytime transmissions (at 06:00 and 12:00) throughout August. Tags were programmed to calculate the proportion of time belugas spent in the 0–1, 0–2, 0–4, and 0–5 m depth bins with a resolution of 0.5 m (Wildlife Computers). Individual averages were weighted based on the number of 6-hour blocks collected for each whale, which were then used to calculate overall averages for each depth bin. Standard errors were calculated using a weighted standard deviation divided by the square root of the number of belugas used in each calculation.

After visual assessment of survey photos into categories for murkiness (non-murky vs murky), we concluded that an availability bias correction based on the 0–2 m depth bin should be applied for whales sighted in the Churchill River (which was identified as having murky water), and a correction factor based on the 0–5 m depth bin would be suitable for the other strata with clear water (see Marcoux et al. 2016). We therefore defined locations in Churchill River (tags never collected dive data in other rivers) for calculation of an availability bias correction factor based on time spent at 0–2 m, and used dive information at all other locations to determine an availability bias based on time spent at 0–5 m for the coastal transects (Figure 1). Location data obtained from the ARGOS system (CLS America) were categorized based on the accuracy of the transmission, varying from class A and B, and 0 to 3. Classes A and B provide no location quality information, Class 0 includes an error range of >1,500 m, class 1, 500–1,500 m, class 2, 250–500 m and class 3, < 250 m (Wildlife Computers). A single location (longitude and latitude) was assigned to each 6-hour time block by choosing the best location (class 3, or 2 if class 3 was unavailable) for that time block. If multiple locations were assigned a class 3 within the 6 hour time block the location closest to the mid-time point was used (9:00 for the morning dive bin and 15:00 for the afternoon dives).

Surface abundance estimates from both the photographic and visual surveys were corrected for availability bias using:

$$\widehat{N}_{corrected} = \widehat{N}_{surface} * C_a$$

where the instantaneous correction factor, $C_a = 1/proportion\ spent\ in\ depth\ bin$, with an associated variance of:

$$var\left(\widehat{N}_{corrected}\right) = \widehat{N}_{corrected}{}^2 \times \left\{\frac{var\left(\widehat{N}_{surface}\right)}{\left(\widehat{N}_{surface}\right)^2} + \frac{var(C_a)}{C_a{}^2}\right\}$$

STOCK ABUNDANCE ESTIMATE

Total stock abundance was estimated by summing the availability bias-corrected abundance estimates (and their associated variances) of the individual strata. 95 % confidence intervals (CI) were calculated assuming a log-normal distribution (Buckland et al. 2001).

RESULTS

SURVEY COVERAGE

Poor weather conditions prevented a complete survey of the Churchill High Density strata on any one day. For analysis purposes, surveys flown over two days (6 August, transects 1–10 and 12 August, transects 9 to 14; Table 1) were combined (the lengths of the replicated transects, 9 and 10, were doubled). One complete survey was flown for both the Nelson High Density stratum (17 August, transects 1–9) and the West Coast Low Density stratum (16 August, transects 1–10). Incomplete surveys of the Churchill High Density and Nelson River strata (just 3 to 5 transects) were flown on other days (Table 1), but weather conditions were inadequate for reliable count data (high winds and white caps). One complete survey was flown of the Seal River Photographic stratum (12 August), while the Churchill River Photographic stratum was surveyed three times (twice on 12 August and once on 19 August; Table 1). Perpendicular distances were missing for approximately 10 % of the visual survey observations.

VISUAL SURVEY

Histograms of the distribution of perpendicular distances indicated an increase in observations after 50 m (Figure 2). Comparison of AIC values of several candidate models indicated the hazard-rate simple polynomial with four adjustment terms provided the best fit, which was improved when data were left-truncated at 50 m and right-truncated at 1200 m (p values for W^2 with uniform weighting and C^2 with cosine weighting were between 0.8 and 0.9). This model estimated a detection probability of 0.32 (SE = 0.037), with an effective strip width of 382 m (Coefficient of Variation [CV] = 0.12). The hazard-rate hermite polynomial model had a ΔAIC of 1.57, although it differed only slightly in detection probability (0.30; SE = 0.038). All other candidate models had ΔAIC values ≥ 5. Inclusion of covariates did not improve model fit, as the distributions of perpendicular distances were similar across the different factors of each covariate (Figures 3 and 4).

Applying the global probability of detection determined from the best-fit model to all observation data (stratified by stratum) provided near-surface abundance estimates of 6,352 (CV = 0.31) in the Churchill High Density stratum, 18,748 (CV = 0.23) in the Nelson River stratum, and 52 (CV = 0.98) in the West Coast Low Density stratum (Table 3). The West Coast Low Density stratum had just one sighting of a lone beluga during the entire survey.

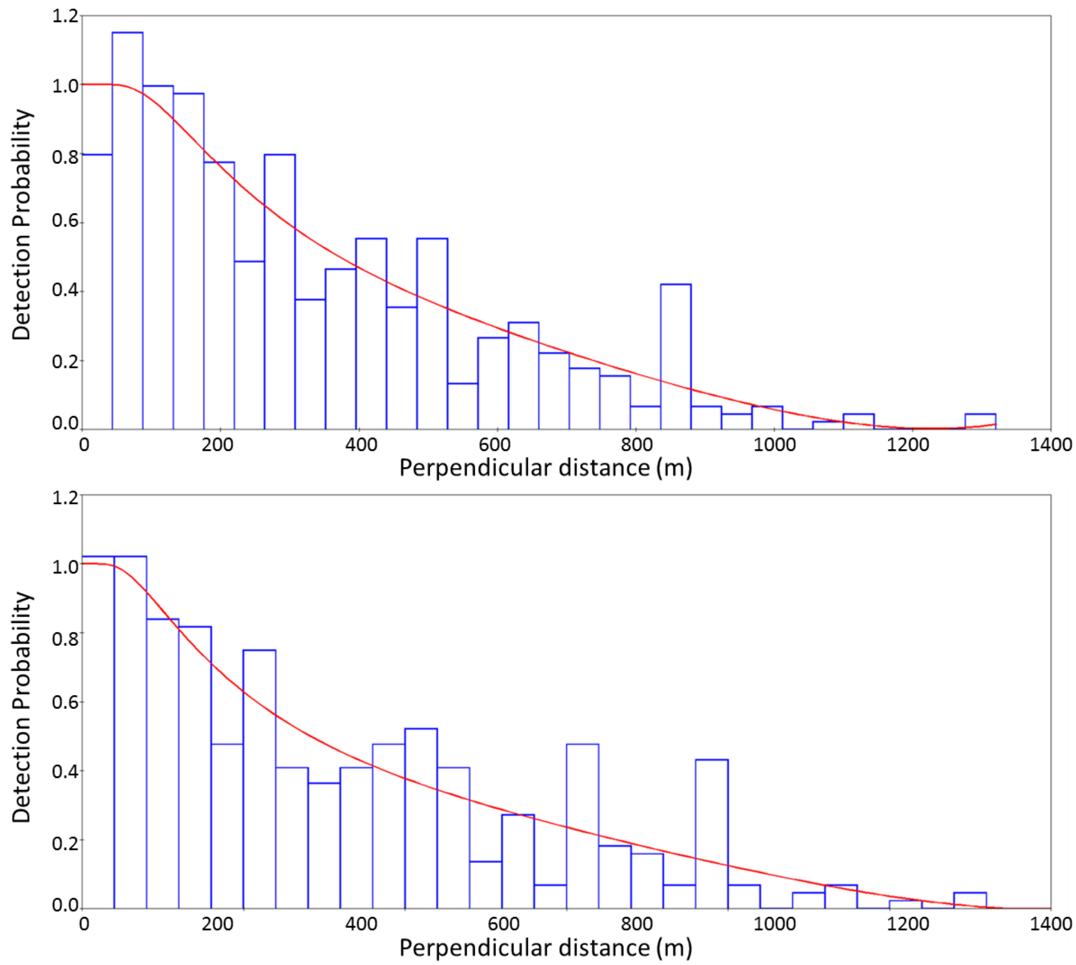

Figure 2. Histogram of perpendicular distances of beluga groups detected in all three visual strata combined (top panel) indicate not all animals were detected within 50 m of the transect line. A hazard-rate simple polynomial function (red line) fit to truncated observations (50 to 1200 m) provided the best fit to the dataset and was used to estimate detection probability (note: perpendicular distances on bottom panel are offset by -50 m).

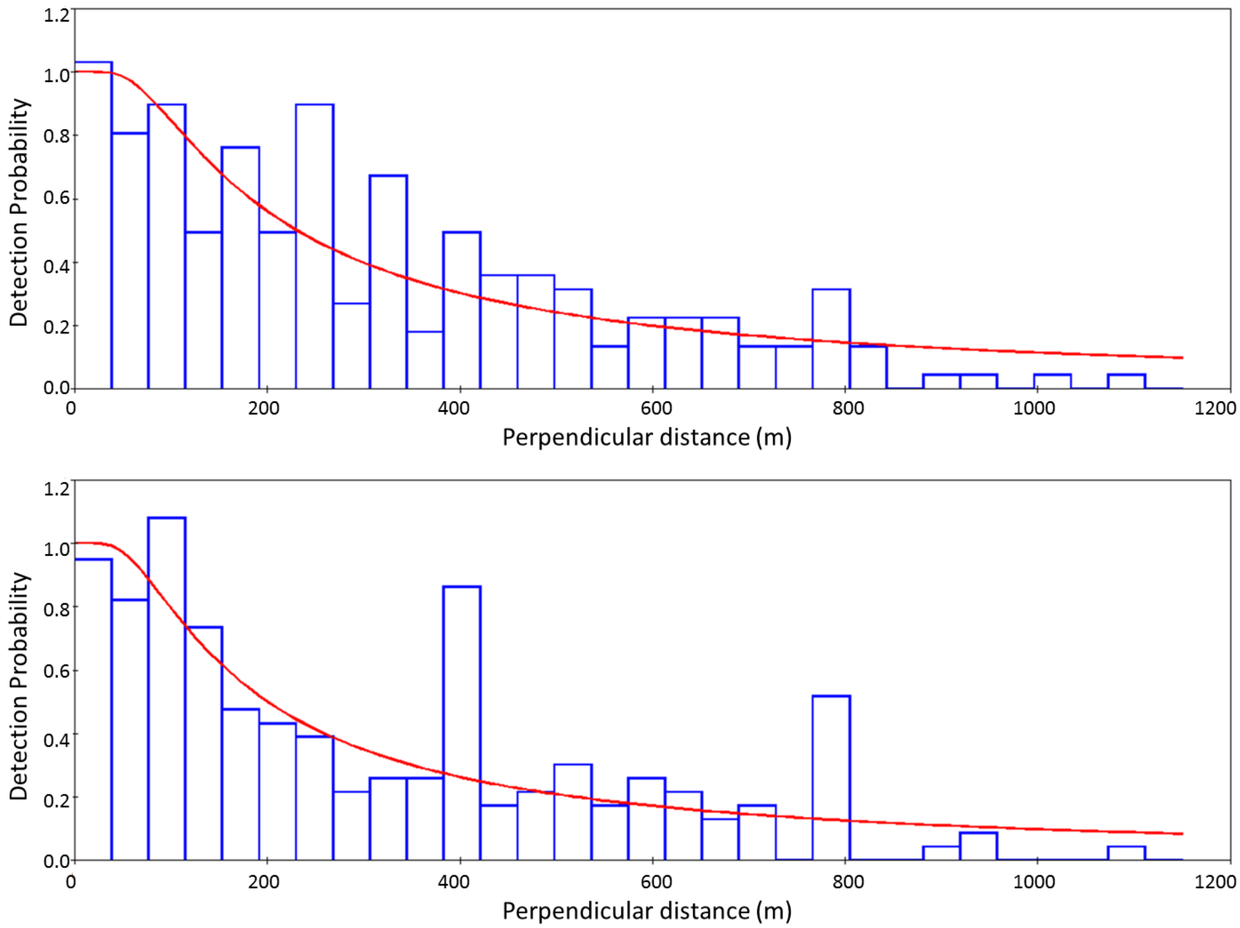

Figure 3. Histograms show similar distributions of perpendicular distances of beluga groups detected by the two primary observers. "Observer" was not retained as a significant covariate in MCDS analysis (note: perpendicular distances are offset by -50 m).

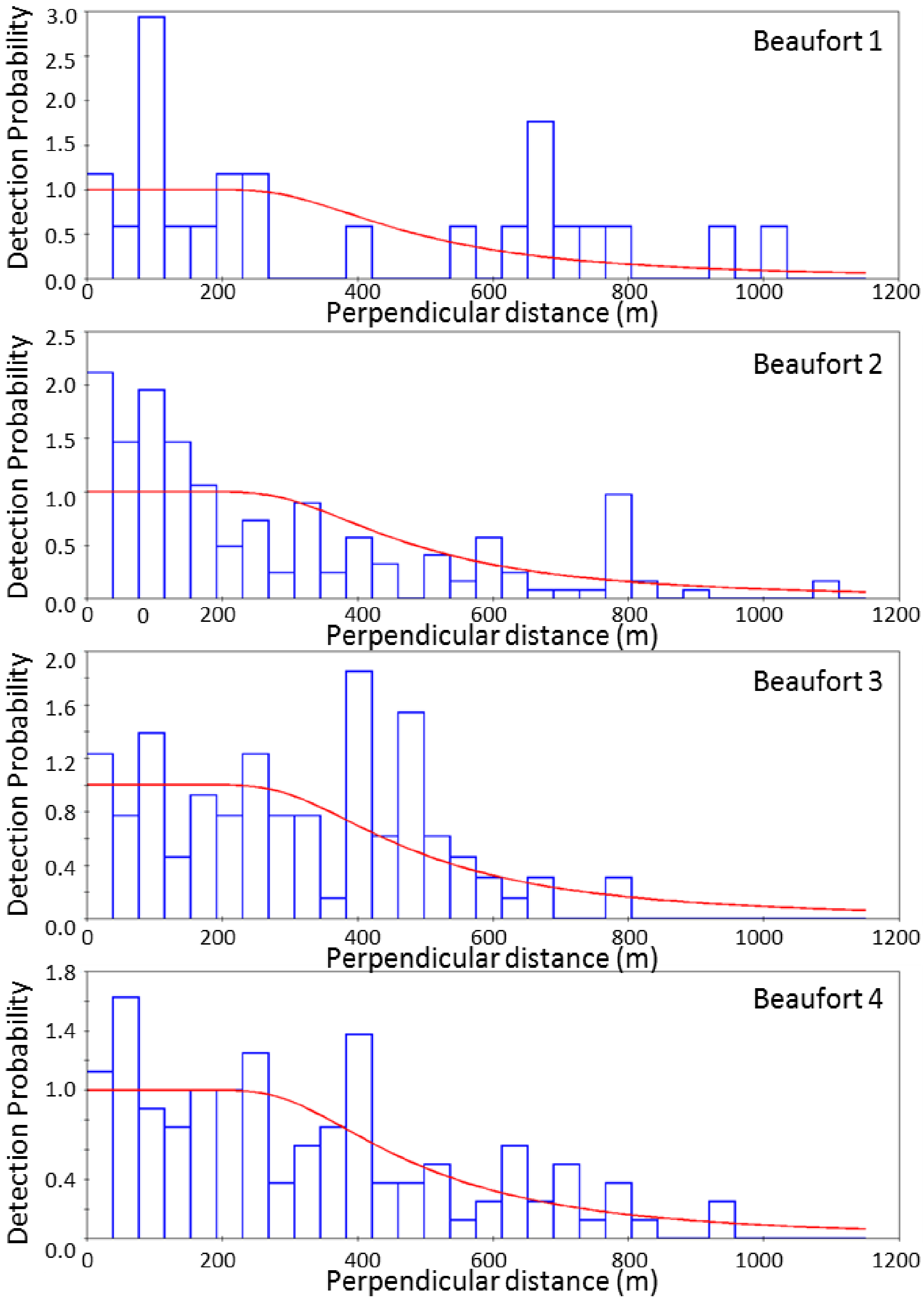

Figure 4. Histograms show similar distributions of perpendicular distances of beluga groups detected across four factors of 'sea state' (1 to 4 from top to bottom). 'Sea state' was not retained as a significant covariate in MCDS analysis (note: perpendicular distances are offset by -50 m).

Table 3. Survey coverage of each stratum. Encounter rate, CV of encounter rate (CVER), mean group size, CV of group size (CVGS), detection probability, and CV of detection probability (CVDP) are provided for visual strata. Surface abundance and CV (CVSA) and corrected abundance for all strata and overall survey region also shown.

Stratum	**Area (km^2)**	**Effort (km)***	**Encounter Rate (groups/km)**	**CV_{ER}**	**Mean Group Size**	**CV_{GS}**	**Detection Probability***	**CV_{DP}**	**Surface Abundance**	**CV_{SA}**	**Corrected Abundance****	**CV_{CA}**
Churchill High Density	*5,598*	*492.9*	*0.21*	*24.6*	*4.16*	*12.9*	*0.32*	*0.034*	*6,352*	*30.7*	*7,876*	*28.9*
Nelson River	*9,119*	*483.2*	*0.70*	*19.1*	*2.25*	*4.5*	*0.32*	*0.034*	*18,748*	*22.6*	*23,248*	*20.0*
West Coast Low Density	*36,095*	*917.2*	*0.0011*	*97.6*	*1.0*†	*n/a*	*0.32*	*0.034*	*52*	*98.2*	*64*	*97.7*
Churchill Photographic	*64*	-	-	-	-	-	-	-	*1,855*	*50.0*	*3,136*	*30.0*
Seal Photographic	*13*	-	-	-	-	-	-	-	*16,249*	*n/a*	*20,149*	*4.0*
TOTAL	-	-	-	-	-	-	-	-	***43,256***	***14.3***	***54,473***	***9.8***

*photographic surveys were complete coverage of the stratum area

**adjusted for availability bias. Correction factor of 1.24 ± 0.05 was applied to all strata except Churchill Photographic, which was adjusted using 1.71 ± 0.11(see text).

†there was only a single whale sighted during the survey of the West Coast Low Density stratum.

PHOTOGRAPHIC SURVEY

Repeat counts of 118 photos were highly correlated (simple linear regression; adj $r^2 = 0.999$, $F_{1,116} = 1.25e+06$, $p < 0.001$). The first and repeat counts were the same for 86 of the 118 photos. The mean percent difference between the counts across all photos was 2.7 %, ranging from 0 to 100 %. The one photo with a 100 % difference had replicate counts of 1 and 2 whales, and when this photo is not considered, the mean percent difference between counts was 1.9 %.

The portion of each photo estimated to be covered by sun glare was the same for 78 of the 118 photos, and differed by 2–5 % for 35 of them, by 10 % for 4 of them, and by 15 % for one of them. Assessment of whether water was murky or not differed for 21 of the 118 photos.

The near-surface abundance for the Seal River photographic stratum was 16,249 whales. The abundance estimates for two photographic surveys of the Churchill River stratum were 928 (Aug 12) and 2,783 (Aug 19) whales (average 1,855, CV = 0.50; Table 3).

AVAILABILITY BIAS

The average percentage of time belugas spent in the 0–5 m bin outside rivers was 80.93 ± 2.95 %, resulting in a correction factor of 1.24 ± 0.05 for the coastal strata (Table 4). The corrected abundance estimates were 7,876 (CV = 0.29) for the Churchill High Density stratum, 23,248 (CV = 0.20) for the Nelson River stratum, 64 (CV = 0.98) for the West Coast Low Density stratum, and 20,149 (CV = 0.04) for the Seal River photographic stratum (Table 3).

The average percentage of time belugas spent in the 0–2 m bin in the Churchill River was 58.34 ± 3.66 %, resulting in a correction factor of 1.71 ± 0.11 (Table 4) and a corrected abundance estimate for the Churchill River photographic stratum of 3,136 (CV = 0.30; Table 3).

Table 4. Average percent of time (± SE) each beluga spent in each of the depth bins in August during the day within the Churchill River, outside the river (coastal), and for the two areas combined.

Churchill River

Deployment Date	Sex	Tag Number	n	Average % time at 0–1 m ± SE	Average % time at 0–2 m ± SE	Average % time at 0–4 m ± SE	Average % time at 0–5 m ± SE
07-08-2015	F	128160	16	40.44 ± 4.65	56.50 ± 4.99	70.50 ± 4.67	75.31 ± 4.00
07-10-2007	M	128161	22	45.14 ± 4.38	60.55 ± 4.20	77.27 ± 3.54	80.41 ± 3.15
07-10-2008	F	128162	22	48.05 ± 4.63	69.00 ± 4.32	86.41 ± 2.83	88.41 ± 2.43
07-11-2008	M	128165	8	38.50 ± 4.04	52.75 ± 5.05	71.00 ± 6.08	78.50 ± 5.75
07-12-2008	M	128157	2	53.00 ± 14.0	70.50 ± 10.5	85.00 ± 4.00	91.50 ± 2.50
07-14-2008	M	128164	18	33.44 ± 5.29	48.61 ± 5.55	66.39 ± 4.74	71.17 ± 4.08
Weighted Average ± weighted SE			89	41.72 ± 2.69	58.34 ± 3.66	74.86 ± 4.12	78.79 ± 3.97

Coastal

Deployment Date	Sex	Tag Number	n	Average % time at 0–1 m ± SE	Average % time at 0–2 m ± SE	Average % time at 0–4 m ± SE	Average % time at 0–5 m ± SE
07-08-2015	F	128160	44	36.61 ± 2.07	53.34 ± 2.32	69.25 ± 2.56	75.45 ± 2.49
07-10-2007	F	128158	62	36.23 ± 1.88	57.15 ± 2.42	74.61 ± 2.21	79.19 ± 2.03
07-10-2007	M	128161	32	30.16 ± 2.09	45.38 ± 2.74	64.00 ± 2.86	69.19 ± 2.83
07-10-2008	F	128162	40	31.10 ± 2.02	49.58 ± 2.47	77.23 ± 2.24	82.65 ± 2.14
07-11-2008	M	128165	54	36.72 ± 1.52	53.02 ± 1.84	71.06 ± 1.91	78.65 ± 1.89
07-12-2008	M	128157	60	40.55 ± 1.40	52.22 ± 1.83	66.52 ± 2.01	75.32 ± 1.91
07-14-2008	M	128164	38	31.32 ± 2.05	48.79 ± 2.68	75.79 ± 2.58	82.00 ± 2.18
07-14-2006	M	128155	61	14.77 ± 0.74	57.07 ± 1.94	97.51 ± 0.37	98.56 ± 0.07
Weighted Average ± weighted SE			391	32.16 ± 2.88	52.83 ± 1.28	75.36 ± 3.65	80.93 ± 2.95

Areas Combined

Deployment Date	Sex	Tag Number	n	Average % time at 0–1 m ± SE	Average % time at 0–2 m ± SE	Average % time at 0–4 m ± SE	Average % time at 0–5 m ± SE
07-08-2015	F	128160	60	37.63 ± 1.95	54.18 ± 2.15	69.58 ± 2.23	75.42 ± 2.09
07-10-2007	F	128158	62	36.23 ± 1.88	57.15 ± 2.42	74.61 ± 2.21	79.19 ± 2.03
07-10-2007	M	128161	54	36.26 ± 2.37	51.56 ± 2.55	69.41 ± 2.38	73.76 ± 2.23
07-10-2008	F	128162	62	37.11 ± 2.32	56.47 ± 2.49	80.48 ± 1.83	84.69 ± 1.66
07-11-2008	M	128165	62	36.95 ± 1.41	52.98 ± 1.71	71.05 ± 1.82	78.63 ± 1.78
07-12-2008	M	128157	62	40.95 ± 1.42	52.81 ± 1.83	67.11 ± 1.99	75.84 ± 1.89
07-14-2008	M	128164	56	32.00 ± 2.17	48.73 ± 2.52	72.77 ± 2.37	78.52 ± 2.07
07-14-2006	M	128155	62	14.84 ± 0.73	57.15 ± 1.91	97.35 ± 0.39	98.53 ± 0.08
Weighted Average ± weighted SE			480	33.97 ± 2.73	53.98 ± 0.97	75.45 ± 3.28	80.73 ± 2.66

STOCK ABUNDANCE ESTIMATE

The sum of the availability bias-corrected abundance estimates of the five strata was 54,473 (CV = 0.098; Table 3).

DISCUSSION

Aerial surveys of beluga abundance are characterized by high variability, which reflects their clumped distribution and high mobility (e.g., movements among strata surveyed on different days). Replicated surveys with a sufficient number of transects per stratum can increase the precision of survey results (Asselin and Richard 2011). Poor weather conditions prevented repeat surveys of all strata except for the Churchill River photographic, and the Churchill High Density stratum was never completely surveyed at one time (Table 1). Near-surface abundance estimates from the replicate surveys of the Churchill River photographic stratum differed substantially (928 on August 12 and 2,783 on August 19). Count differences could reflect collective behavioural differences that influence the amount of time belugas spent near the surface, or movement of animals in and out of the river. There is some evidence to suggest beluga presence in river estuaries is related to tidal patterns (Caron and Smith 1990, Ezer et al. 2008). The August 12 survey was conducted at 18h45, when the Churchill River was at peak high tide (18h37), while the August 19 survey was conducted at 13h49, which was about midway between high (10h40) and low (16h27) tides. A higher count during the falling tide is contrary to studies that have found belugas move in the direction of the tide (e.g., Ezer et al. 2008), or that have detected more beluga calls during high tide (Castellote et al. 2013, Simard et al. 2014). Hansen (1988) found beluga abundance in the Churchill River estuary was positively related to the difference between the maximum estuarine temperature and coastal temperature, which are not available for our survey dates. Differences in water clarity between high and outgoing tides could affect detection of belugas in photos, but examination of photos for murkiness did not identify any differences between the two survey dates.

Poor weather also caused gaps of several days between surveys of adjacent strata. Ideally, adjacent strata are surveyed back-to-back to minimize the impact of non-random animal redistribution on counts. Non-random redistribution among strata could be a potential problem for abundance estimates in the Churchill High Density stratum, which was surveyed on August 6 and 12, and the Seal River photographic stratum it encompasses, which was surveyed on August 12. A group of killer whales (*Orcinus orca*) were sighted at Whale Cove, Nunavut, approximately 400 km north of our survey area, on August 12 (DFO, unpublished data). Both belugas and narwhals are known to aggregate near the coastline in the presence of killer whales (Reeves and Mitchell 1988), which can travel distances up to about 250 km day^{-1} (Matthews et al. 2011). Richard (2005) attributed dense aggregations of beluga whales in the Churchill High Density stratum to the presence of seven killer whales sighted in the area during the survey. Given the time between surveys, it is possible that whales were spread throughout the Churchill High Density stratum on August 6, but aggregated in the Seal River stratum on August 12 (perhaps in response to killer whale presence), which would have resulted in double-counting and an overestimate of abundance. Re-analysis using only the Churchill High Density observations from August 12, which included five transects surveyed on the same day as the Seal River, results in an approximate 25 % increase in estimated abundance for that stratum (uncorrected surface abundance of 8,992 for the August 12 survey vs 7,192 for the combined August 6 and 12 surveys). This does not suggest movement of large numbers of whales from the Churchill High Density stratum into the Seal River photographic stratum occurred between the two survey dates (in fact, the aggregation of belugas at the mouth of the Seal River persisted throughout the duration of the study; Table 1). Furthermore, the eight satellite-tagged beluga whales did not show any directed movements over the duration of the surveys (DFO unpubl. data).

Near-surface abundance estimates from visual and photographic surveys are biased in two ways: some animals available for detection are missed by observers or photo readers (perception bias), and some animals are not visible to observers due to the fact they were too deep in the water column while within visible or photographic range of the aircraft (availability bias). It was not possible to correct visual survey estimates for perception bias using only observations from front observers, as estimation of the proportion of animals detected at the surface requires comparison of counts by two independent observers on the same side of the aircraft (Buckland et al. 2004). Estimates of perception bias based on surveys of belugas in the North Water Polyna (Heide-Jørgensen et al. 2013) and Cook Inlet, Alaska (Hobbs et al. 2000) indicate 2 to 8 % of belugas are missed during visual surveys. Perception bias is reduced to even lower levels in photographic surveys since readers have much more time to examine the image (J-F. Gosselin, DFO, pers. comm.). Close agreement between repeat counts by the same photo reader indicates perception bias has minimal impact on our photographic survey abundance estimates (treating the repeat counts as independent, given the several months between them). Gosselin et al. (2014) similarly reported low inter-reader variability between two readers of approximately 3 %, and concluded the bias of perception error on abundance estimates from photographic surveys is minimal.

Availability bias corrections can increase near-surface estimates of marine mammal abundance by two to five-fold (e.g., Watt et al. 2015). Concurrent collection of survey and tagging data allowed us to remove both spatial and temporal uncertainty in whale dive behaviour, which can vary regionally and seasonally in response to changes in habitat or foraging tactics (e.g., Martin et al. 2001). Kingsley and Gauthier (2002) used detailed dive data from time-depth-recorders of St Lawrence beluga dive behaviour to calculate an availability bias of 47.8 % in silted waters (Kingsley and Gauthier 2002), or a correction factor of 2.09. Marcoux et al. (2016) calculated a similar factor of 2.06 for the 0–2 m bin for Cumberland Sound whales. Our smaller correction for the 0–2 m depth bin in murky areas (1.71) indicates WHB beluga whales spent more time at the surface than belugas in the other study locations. This may simply reflect the shallow bathymetry of western Hudson Bay (Pelletier 1986), and the preference of belugas for shallow water in the survey area (see Martin et al. 2001). The near-surface behaviour of WHB belugas may also have been influenced by the presence of killer whales within western Hudson Bay at the time of the survey. Our use of dive and location data from whales to calculate site-specific correction factors based on water clarity in each stratum represents an improvement over previous surveys by reducing uncertainty in the corrected abundance estimate. While we consider our availability correction factor to be appropriate for this survey at the time it was conducted, we caution that it is based on a sample of whales assumed to represent the behaviour of the stock.

The availability bias correction factor applied to our surface abundance estimates is appropriate for instantaneous sightings (i.e., photographs). For visual surveys, there is a longer period of time that a diving animal can appear at the surface and be detected by the observer, and application of an instantaneous correction factor may lead to a positive bias in visual survey estimates (i.e., requires a lower availability bias correction factor). Availability bias correction factors that incorporate the dive cycle of the animal (time for a complete dive cycle and time at surface per dive cycle) and the search time of the observer have been developed (see McLaren 1961, Asselin et al. 2012). Dive data from our tags, however, are recorded as percentages of time spent within a given depth bin over 6 h periods; we therefore require more detailed information on dive cycles of WHB belugas before fine-tuning our correction factor for visual surveys.

Application of different availability bias correction factors limits direct comparison of WHB beluga stock abundance estimates in 2004 and 2015, and comparison of both surveys to the 1987 survey is further complicated by different survey area coverage (Richard 2005, Richard et al 1990). The five strata surveyed in 2015, however, were surveyed in 2004 with similar coverage and effort (Richard 2005). The near-surface (i.e., not corrected for availability bias) abundance estimates for these strata was 43 256 (CV = 0.14) in 2015 and 40 989 (CV = 0.31) in 2004 (Table 5). The larger estimate for the aggregation of belugas at the mouth of Seal River, and lower estimates for the larger surrounding strata, Churchill High Density and West Coast Low Density, in 2015 vs 2004 suggest belugas were more aggregated in 2015 (although the differences are within the associated error).

Table 5. Comparison of surface abundance estimates (not corrected for availability bias) for the five strata surveyed in 2015 and 2004. 2004 data can be found in Table 1 of Richard (2005).

Stratum	**2015 Surface Abundance (CV)**	**2004 Surface Abundance (CV)**
Churchill High Density	6,352 (30.7)	12,027 (96.0)
Nelson River	18,748 (22.6)	17,544 (28.2)
West Coast Low Density	52 (98.2)	1,753 (79.9)
Churchill Photographic	1,855 (50.0)	2,076 (40.6)
Seal Photographic	16,249 (n/a)	7,589 (17.3)
TOTAL	**43,256 (14.3)**	**40,989 (30.1)**

ACKNOWLEDGEMENTS

Thank you to Robert Karatek and Leo Ikhakik for their assistance conducting surveys, and to J-F Gosselin (DFO) for advice on visual survey analysis. Thank you to the staff at the Churchill Northern Studies Centre for accommodating us during our extended stay in Churchill, and to the Kenn Borek flight crews and the Polar Continental Shelf Program (PCSP) for aircraft and logistical support. Funding for this project was provided by DFO, PCSP, the Nunavut Wildlife Management Board (NWMB), and Oceans North Canada.

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