SCIENCE REVIEW OF NARWHAL (*MONODON MONOCEROS*) SURVEYS CONDUCTED BY GOLDER-WSP IN 2019–2023 FOR USE IN FISHERIES STOCK ASSESSMENTS

CONTEXT

The Baffinland (BIM) Mary River Project is an operating open-pit iron ore mine located on North Baffin Island in Nunavut. As part of their project certificate, annual surveys of narwhal (*Monodon monoceros*) have been conducted by Golder Associates Ltd. (hereafter Golder) and WSP Canada Inc. (hereafter WSP) in Eclipse Sound and Admiralty Inlet in August 2019, 2020, 2021 (Golder Associates Ltd. 2020a, 2021, 2022), and 2022 and 2023 (WSP Canada Inc. 2023, 2024).

Fisheries and Oceans Canada (DFO) Science is responsible for providing advice on the sustainable hunt of these stocks. DFO surveys and subsequent population modelling rely on surveying narwhal aggregations when they are in their summering grounds. A time series of abundance estimates provides robust population dynamics modeling for stock assessment. Therefore, this document reviews the Golder-WSP surveys and resulting abundance estimates for use in future population dynamics models.

Golder-WSP conducted surveys during the open water and shoulder seasons (before ice break-up in the spring and after ice formation in the fall); this review focuses only on those surveys in the open water season (namely August). The August surveys conducted by Golder-WSP are described briefly and reviewed here. Recommendations on final abundance estimates that could be included in future population dynamics models are presented.

This Science Response Report results from the regional peer review on October 16, 2024, for the Science Review of Narwhal (*Monodon monoceros*) Surveys Conducted by Golder-WSP in 2019-2023 for use in DFO Fisheries Stock Assessments.

ANALYSIS AND RESPONSE

Golder-WSP survey methods

Survey design

The Eclipse Sound surveys were designed as systematic line transects with survey lines 8.6 km apart for Eclipse Sound East and Pond Inlet strata, 4.3 km for the Eclipse Sound West stratum, 10 km for the Navy Board Inlet stratum, and 4 km spacing for the Milne Inlet North stratum (see Figure 1). Tremblay Sound and Milne Inlet South strata, which typically have large aggregations of narwhal, were surveyed as complete-coverage photographic surveys. Reconnaissance surveys were also conducted in the fjords and bays off Eclipse Sound.

The Admiralty Inlet surveys were divided into three strata (Admiralty Inlet North, Admiralty Inlet South, and Admiralty Fjords) (Figure 1). Systematic transects spaced 8.5 km apart were flown in Admiralty North and South strata, and reconnaissance surveys were flown in the fjords.

Surveys were repeated as many times as the weather permitted. However, the data analysis was only completed for surveys with complete coverage and adequate survey conditions.

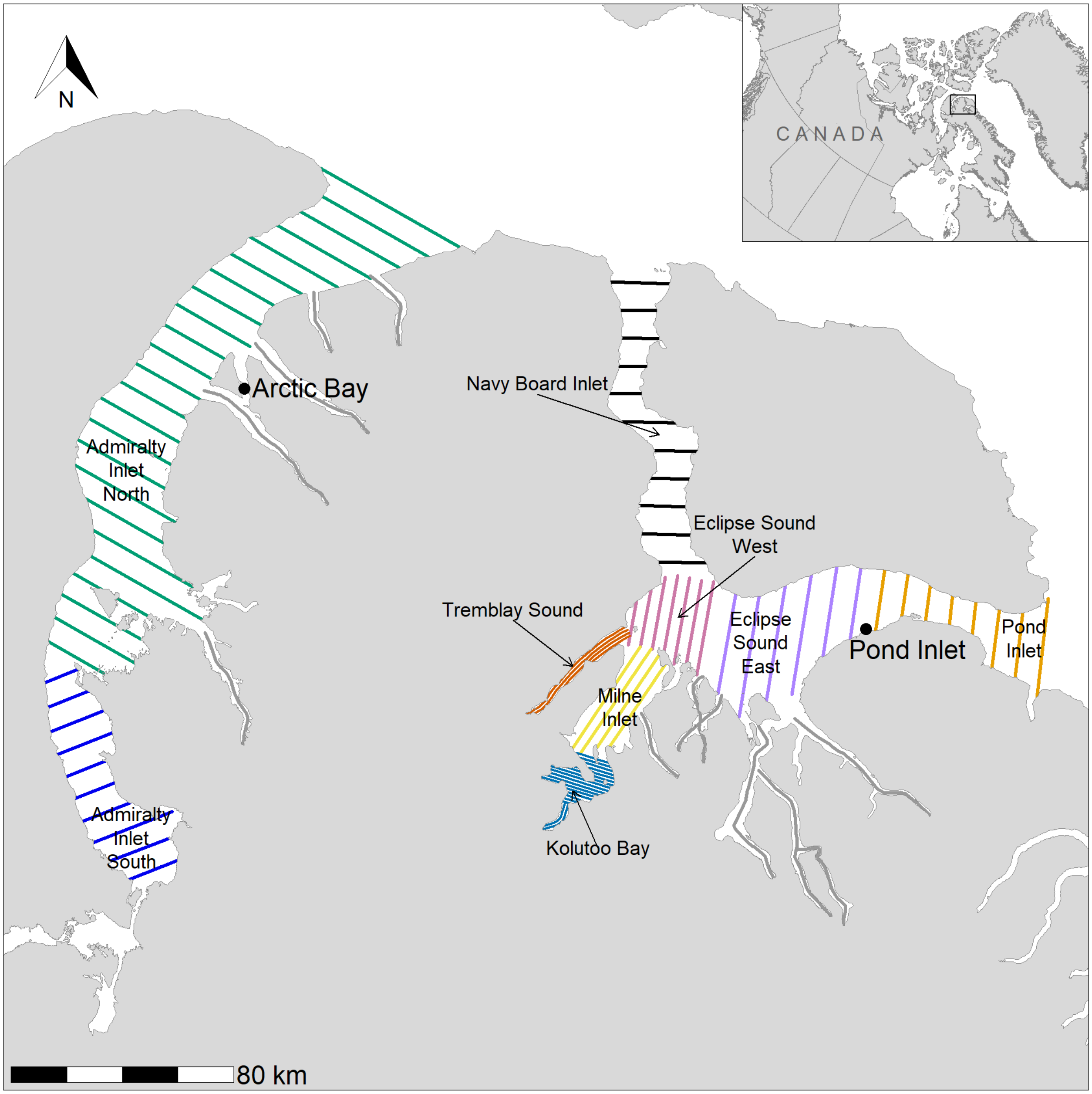

Figure 1. Map of the survey area and design with planned survey transects (adapted from Golder Associates Ltd. (2021) but utilized in all Golder-WSP surveys from 2019-2023).

Visual Survey

Surveys followed methods developed and used by DFO (e.g., Doniol-Valcroze et al. 2015). All surveys were flown in de Havilland Twin Otters (DH-6) at an altitude of 305 m (1,000 ft) and a ground speed of 185 km/h (100 kn). Surveys were designed as a double-platform experiment with two primary observers and two secondary observers at bubble windows. The two observers stationed on the same side of the aircraft were isolated visually and acoustically. All observers recorded narwhal groups, group sizes, and perpendicular declination angles (to calculate perpendicular distance from the trackline). Primary observers also recorded environmental conditions including ice concentration, sea state, fog, and glare. These environmental conditions were recorded at the start and end of each transect. Photographs were taken during the visual survey to supplement visual sightings for missed clinometer angles and group sizes.

If large aggregations (e.g., > 50 narwhal or when observers indicated they could not accurately keep up with narwhal counts) were identified during visual transects, the survey team ended visual survey methods and initiated a photographic survey protocol (see below for more detail about photographic methods) of the entire narwhal aggregation using pre-planned survey grids. The photographic survey ended after they had achieved complete coverage of the aggregation.

Photographic Survey

Photographic surveys were conducted at an altitude of 610 m (2,000 ft) and a ground speed of 185 km/h (100 kn). Aircraft were equipped with an optical glass-covered camera hatch at the rear and two identical camera systems. The cameras were connected to a laptop computer to control exposure settings and photograph interval. The cameras were oriented widthwise (long-side perpendicular to the trackline) and angled obliquely at 25-27°. The interval between photographs was set to maintain an overlap (on the inside edge) of approximately 15-30% (depending on survey year) between two consecutive photographs. The overlap between consecutive photos was larger on the outside edge given the trapezoid projection of the photos. The camera models and lenses differed between 2019-2022 and 2023 and are detailed in Table 1.

Table 1. Camera characteristics.

Survey year	Model	Type	Lenses	Focal length (mm)	Sensor length (mm)	Sensor width (mm)	Image size (Mega-pixels)	Camera angle (°)
2019-2022	Canon EOS 5DS R	Single lens reflex	Sigma 35 mm f/1.4 DG HSM Zeiss 35 mm f1.4 Milvus ZE	35	35.9	24	50.3 (8.7 x 5.8)	27
2023	Fujifilm GFX 100s	Large format	Fujifilm 45 mm f/2.8 WR	45	45.8	32.9	102 (11.6 x 8.7)	25

Distance Sampling Analysis

For the visual components of the survey, mark-recapture distance sampling (MRDS) analyses were performed using the perpendicular distance of narwhal group detections. Duplicate sightings from primary and secondary observers were determined based on the timing of the sighting (within 10 seconds) and the perpendicular declination angle (less than 10° difference between sightings). When group size differed between primary and secondary observers, the largest group size was used in analysis (except for the surveys in 2019 where they used the primary observer's group size). Point independence MRDS analyses were performed using the MRDS (Laake et al. 2018) package in R (version 3.6.2 in 2019 and 2020 [R Core Team 2019] and version 4.1.2 in 2021, 2022 and 2023 [R Core Team 2021]). Environmental and observer covariates were included for fitting the detection function and mark-recapture models. Models were selected using the minimum Akaike's Information Criterion (AIC).

Photographic Analysis

Photographs were orthorectified based on the camera angle and the tilt of the plane prior to being examined in ArcMap 10.1 (Esri). Water clarity was evaluated in each photo and classified as either murky (water in which narwhal could only be observed at the surface) or clear (water in which narwhal could be observed down to 2 m) in order to apply the availability bias adjustment (see below). For the 2019 survey, a senior experienced photo analyst with eight years of experience in photographic analysis trained three readers with diverse levels of experience. The three trainees collaboratively read the photos to detect the presence of narwhals. A random subset of photos was re-analyzed by the senior photo analyst to evaluate reliability and repeatability. For the later surveys, one of the trainees from the 2019 survey examined all the photos to detect narwhals. A randomly selected subset of the photos (in 2020, 2021, 2022) or all the photos (in 2023) were re-analyzed by a second experienced photo analyst to evaluate reliability and repeatability.

The area covered by each photograph was calculated in ArcMap based on the altitude, the focal length of the camera sensor, the length and width of the camera sensor, the angle of the camera, and the tilt of the aircraft. When present, the area covered by land was subtracted from each photograph. Photograph readers also identified areas where the sun's glare made it impossible to evaluate if narwhals were present and these areas were removed from the photograph. The density of narwhal was calculated as the sum of narwhals found in all photographs divided by the sum of the area of all the photographs. The total number of narwhals was estimated by multiplying narwhal density by the total water area in all the merged photographs (i.e., with overlap areas removed so that no area of water was included more than once).

Availability and Perception Bias

Surface estimates were adjusted to account for narwhal that were underwater during the time of the survey and could not be counted by the survey observers or the photograph readers (availability bias correction, C_a). Correction factors were those used by previous DFO aerial surveys (Doniol-Valcroze et al. 2015, Marcoux et al. 2016). For the photographic survey, correction factors of 3.18 (coefficient of variation [CV] = 0.03) for mid-August and 3.16 (CV = 0.03) for late August (from Watt et al. 2015) were used. For the visual surveys, correction factors adjusted for time in view were used: 2.94 (CV = 0.03) for mid-August and 2.92 (CV = 0.03) for late August (from Doniol-Valcroze et al. 2015). Availability bias corrections were applied at the trackline.

A perception bias adjustment was calculated using a double platform mark-recapture distance sampling analysis (see above).

Golder-WSP Survey Results

2019 Survey

In 2019, five replicate surveys were conducted; three (surveys 3, 4 and 5) had complete coverage of the survey design in Eclipse Sound and were analyzed (see Figure 24-A, 25-A, and 26-A in Golder Associates Ltd. 2020a). Survey 3 was flown August 21-22, survey 4 was flown August 25-27, and survey 5 was flown August 29-30 (see Table 11 in Golder Associates Ltd. 2020a).

There were 414 narwhal sightings in Eclipse Sound that were used to estimate a detection function. Due to lower detection along the trackline (as opposed to 200 m from the trackline) in Eclipse Sound, a gamma detection function was selected, in MRDS, and data were right-truncated at 1,200 m (i.e., sightings beyond 1,200 m were not included in defining the detection function). The best distance sampling model had a gamma key function and covariates for glare, aircraft side, and Beaufort sea state (they used the Beaufort Wind Force Scale but called it Beaufort sea state) (g(x) = 0.42 [CV = 0.04%]) (see Figure 27 in Golder Associates Ltd. 2020a for a histogram of perpendicular distances in Eclipse Sound).

Mark-recapture model selection with the lowest AIC included two covariates: the number of observer sightings in the previous 30 seconds, and the interaction between aircraft side and observer. The model resulted in a p(0) of 0.60 for observer 1 and 0.38 for observer 2, and a combined p(0) of 0.74 (CV = 0.07), which resulted in a detection probability of 0.31 (CV = 0.07).

Reconnaissance surveys were not described in the document, but 912 km was covered in fjords in Admiralty Inlet and no narwhal were observed (see Table 18 in Golder Associates Ltd. 2020a).

Of the five replicate surveys conducted in 2019, only survey 5 had complete coverage in Admiralty Inlet (see Table 11 in Golder Associates Ltd. 2020a), but Golder Associates Ltd. (2020a) reasoned that using surveys 3, 4, and 5 would be best since those surveys were also analyzed for Eclipse Sound; survey 3 covered ~ 75% of the survey design in Admiralty Inlet, and survey 4 covered 55%. The survey was switched to photographic over a small area in Admiralty Inlet during survey 5.

There were 473 narwhal sightings in Admiralty Inlet that were used to estimate a detection function. Data were right-truncated at 900 m. The best-fit model was a gamma function with covariates for the interaction between observer and Beaufort sea state, glare, and the number of observer sightings in the previous 30 seconds (g(x) = 0.39 (CV = 0.03) (see Figure 30 in Golder Associates Ltd. 2020a for histogram of perpendicular distances in Admiralty Inlet).

A detection function was created for narwhal in the photographic surveys as there was a slight decrease in sightings with increased distance from the trackline. The detection model for the 305 m photographic surveys, which only occurred for three surveys in Admiralty Inlet when survey protocol changed from visual to photographic due to a large narwhal aggregation, resulted in a probability of detection of 0.86 (correction factor of 1.17 (CV = 0.03), n = 571) (see Figure 40 in Golder Associates Ltd. 2020a). The detection model for the other photographic surveys flown at 610 m, Eclipse Sound and Admiralty Inlet together, resulted in a probability of detection of 0.83 (correction factor 1.20 (CV = 0.02), n = 987) (see Figure 41 in Golder Associates Ltd. 2020a).

2020 Survey

In 2020, the survey team completed four replicates of the Eclipse Sound area. However, only two were analyzed and presented (August 20-21 [survey 1] and August 28-29 [survey 3]) in the Golder report (Golder Associates Ltd. 2021). Survey 2 missed the top half of Navy Board Inlet due to poor sighting conditions. Survey 4 was completed in two days due to high sea states encountered on the first day. Thus, Golder argued to exclude surveys 2 and 4 from further analysis; however, survey 4 sighting conditions were Beaufort sea state 3 or less for 85% of the survey. A total of 230 sightings and 405 individual narwhals were recorded during the visual survey (Table 10 in Golder Associates Ltd. 2021). A total of 3,464 sightings and 5,916 narwhals were recorded during photographic surveys (Table 12 in Golder Associates Ltd. 2021).

For the Admiralty Inlet area, two replicates were completed, one on August 20-21 and the other on August 28-29, which coincided with the replicates retained for Eclipse Sound (Golder Associates Ltd. 2021). There were 845 narwhal sightings and 1,390 individual narwhals recorded during the visual survey (Table 11 in Golder Associates Ltd. 2021). There were 8,315 sightings and 11,300 narwhal recorded during the photographic survey in Admiralty Inlet (Table 12 in Golder Associates Ltd. 2021). The model with the lowest AIC for the detection function included a hazard rate key function and the covariates for observer, 30 second rolling count of observation, and the interaction of glare intensity, side of aircraft and glare angle (g(0)

= 0.49, CV = 0.03). The model with the lowest AIC for the mark-recapture analysis had the covariates glare intensity, 60 second rolling count of observation, and interaction between observer and distance (p(0) = 0.73 for observer 1, p(0) = 0.73 for observer 2, and combine p(0) = 0.92, CV = 0.02). The combined models resulted in a detection probability of 0.46 (CV = 0.04).

2021 Survey

In 2021, the survey team conducted five replicates of the Eclipse Sound survey; however, only three replicates had complete coverage and were analyzed (surveys 1 and 2 combined, 4 and 5; Table 13 in Golder Associates Ltd. 2022). Surveys 1 and 2 were combined due to technical issues with the cameras on one of the aircraft. Survey 3 was not analyzed due to low ceilings and high Beaufort sea state. For the Admiralty Inlet area, four replicates of the survey were flown, but only two were retained for analysis (survey 3 and 4; Table 16 in Golder Associates Ltd. 2022). Surveys 2 and 5 were not analyzed due to poor observation conditions. Environmental conditions for the surveys were presented by Golder (Golder Associates Ltd. 2022) for both areas combined. For survey 2, 85% of the effort was conducted under a Beaufort sea state of 3 or less.

The model with the lowest AIC for the detection function included the half normal key function with the covariates for observer pair, glare angle, and the interaction of glare intensity, 30 second rolling count of observations, and group size (g(x) = 0.36, CV = 0.04%). For the mark-recapture analysis, the model with the lowest AIC included the covariates for observer, distance, observer pair and the interaction of distance, 15 second rolling count of observations, and group size (p(0) of 0.69 for observer 1, p(0) = 0.57 for observer 2, and combined p(0) of 0.86, CV = 0.03). The combined models resulted in a detection probability of 0.31 (CV = 0.05).

Approximately 81% of survey 3 was conducted under a Beaufort sea state of 3 or less, and 6% of the survey had light to thick fog. For survey 5, the fog was negligible, and 72% of the effort was conducted under a Beaufort sea state of 4 or less.

Survey 4 was the only survey that covered both Admiralty Inlet and Eclipse Sound. Therefore, the report suggests using survey 4 for the abundance estimate. Survey 4 also had the highest abundance estimate (2,595 vs 2,172 and 1,410 for surveys 2 and 5, respectively). The report also argues that survey 4 is preferred because it has the smallest CV since the majority of the narwhal sightings were made in the photographic part of the survey. However, an argument could be made that the photographic portion of the survey generally underestimates the error around the estimate and the CV values for the photographic survey should be revised.

For the Admiralty Inlet area, only surveys 3 and 4 were completed. The other surveys were not fully completed due to poor or deteriorating survey conditions. The figures and numbers reported for the different survey conditions combined Eclipse Sound and Admiralty Inlet data. Without the raw data, it is impossible to assess the survey conditions of each area separately.

2022 Survey

For Eclipse Sound, the abundance estimates were calculated for three survey replicates (surveys 2, 3, and 4, Table 2). Survey 1 was incomplete due to deteriorating survey conditions which caused the survey to be terminated early. Survey 2 had high Beaufort sea states in Navy Board Inlet (Beaufort sea state of 4–6 for 80% of effort) and western portions of Eclipse Sound (Beaufort sea state of 4–6 for 35% of effort). In addition, the abundance estimate from survey 2 was significantly lower than the other two replicates. For this reason, WSP excluded this survey from their abundance estimate calculation.

For Admiralty Inlet, two survey replicates were completed (surveys 2 and 3), generating 929 visual narwhal sightings and 11,636 narwhal detections in the photographs. Both surveys were used in the abundance estimate.

Generally, the Beaufort sea state was recorded between 0-3 in both survey areas. If sea state conditions exceeded Beaufort 4, the area was generally abandoned, and the survey ceased.

The distance sampling model selected had a half-normal key function, including a second order cosine adjustment term with covariates glare cover, glare intensity and observer team. The factors observer team and observers were included in the mark-recapture model, resulting in a p(0) of 0.78 for observer 1, 0.29 for observer 2, and a combined p(0) of 0.83 (CV = 0.06). The combined models yielded a detection probability of 0.39 (CV = 0.08).

2023 Survey

Two replicates of the Eclipse Sound area were completed in 2023 (surveys 1 and 3) while one replicate of the Admiralty Inlet was completed (survey 2; Table 2). Eclipse Sound survey 1 was completed in two days and covered all the planned survey strata, while survey 3 was completed in three days. Two transects on the northern part of Navy Board could not be completed during survey 3; however, no narwhals were detected on these transects during survey 1.

Survey 2 in Admiralty Inlet was also completed in two days but did not cover all the planned survey transects due to fog and high Beaufort sea states. Visual sightings of narwhals from Eclipse Sound and Admiralty Inlet were combined to fit the detection function for the distance sampling model because all surveys had the same observers. Distance data were right-truncated at 900 m.

The distance model with the lowest AIC value had a gamma key function and included the covariates observer pair (also referred to as observer team in the text), Beaufort sea state, ice cover (%) and fog intensity ranking. The mark-recapture model selected included the covariates observer, distance, observer pair, and interaction factors between

1. Beaufort sea state and turbidity,
2. glare covering angle and rolling count of observation within 60 seconds of the observation and
3. distance and glare covering angle.

The mark-recapture model resulted in a p(0) of 0.79 for observer 1, 0.40 for observer 2 and a combined p(0) of 0.86. The combined distance and mark-recapture models yielded a detection probability of 0.339 (CV = 0.056).

Approximately 98% of the total survey effort occurred in Beaufort sea states between 0 and 4. The survey was suspended when sea state conditions exceeded Beaufort sea state 4.

Table 2 provides an overview of all the survey results in Golder Associates Ltd. (2020a, 2021, 2022) and WSP Canada Inc. (2023, 2024).

Review

Methods

Some elements of the methods used by Golder-WSP may generate a positive abundance bias. For example, for duplicate sightings from the MRDS analysis, when the two observers disagreed in their estimation of group size, Golder-WSP took the larger group estimate instead of taking an average or the estimate from the primary observer, who is typically the most experienced observer (e.g., Borchers et al. 1998), except in 2019 when they took the primary observer's group size. A comparison between narwhal group size estimated by aerial survey observers and from photo analysts of the same narwhal groups in Greenland showed that the group sizes estimated from visual survey observers were larger than the ones estimated by the photo analysts (Bröker et al. 2019). While the real group size was unknown, using the larger group estimate might not represent an accurate estimate of group size and might positively bias the final estimated abundance. Uncertainty in group size, depending on the magnitude, can have an impact (± 5%) on the resulting abundance estimate (Hamilton et al. 2018); however, methods could be explored to account for this uncertainty (Clement et al. 2017).

The water clarity of each photograph was evaluated subjectively by each observer. DFO Science recommends using an objective method to evaluate water clarity, such as using a colour palette against the photographs to define a clarity level (Watt et al. 2021), measuring turbidity in various zones and dividing the strata into those defined turbidity zones (Lesage et al. 2024), or using remotely sensed data to assess turbidity (Dogliotti et al. 2015). In addition, turbidity could be recorded during the visual line transect surveys and then incorporated into detection probabilities. Water clarity determines the availability bias adjustment factor used to adjust the survey and has a large impact on the resulting abundance estimate.

Data analysis

Golder-WSP removed survey replicates for various reasons that are not standardized or predetermined. For example, for the Eclipse Sound survey in 2019, Golder-WSP excluded survey 5 because a large aggregation of narwhal may have been missed (see Table 17 in Golder Associates Ltd. 2020a). It is an assumption of aerial survey design that the density of animals in the area not covered by the survey can be predicted by the density of animals in the area covered by the survey. This extrapolation is supported by the uniform placement of lines from a random start point that ensures that the habitat covered by the survey is as similar as possible to the habitat in the remaining unsurveyed area (Buckland et al. 2004, Fewster et al. 2009). Golder did not demonstrate that this assumption was not valid for this survey, instead making an arbitrary determination to exclude survey 5 on speculation. In 2020, Golder excluded survey 2 for incomplete coverage. They also excluded survey 4 because of unfavourable survey conditions. However, the conditions cannot actually be determined from the figures they provide, which amalgamate conditions in both Admiralty Inlet and Eclipse Sound. Ideally, a consistent threshold could be defined to determine what surveys should be included in the abundance estimate, rather than the ad hoc approach that has been applied.

Golder-WSP used the survey replicates with the highest estimated abundance as their best abundance estimate (e.g., Golder Associates Ltd. 2021, WSP Canada Inc. 2024); however, an average of the replicates is the best method to account for variability in narwhal diving behaviour and distribution over the survey period (e.g., Huber et al. 2001, Siebert et al. 2006, Lowry et al. 2008, Gosselin et al. 2014, Marcoux et al. 2016, Watt et al. 2021). For instance, individual surveys, even within a few days or even on the same day, can have variable abundance estimates (e.g., Lowry et al. 2008, Gosselin et al. 2014, Marcoux et al. 2016). However, the availability bias adjustment factors are based on the average time that animals spend at the surface and underwater over periods of days to weeks. Therefore, higher adjusted abundance estimates based on survey replicates may represent times when narwhals spend a larger proportion of their time at the surface or survey replicates when observers encountered larger clusters of narwhals on, rather than between, survey lines.

Another positive abundance bias potentially results from the photographic analysis. On average, the realized photographic overlap (including consecutive photograph overlap and overlap of photographs between transect lines) was 52% in 2019, 65% in 2020, and 45% in 2021. In 2022 and 2023 they do not report the realized photographic overlap but note that the target overlap is

15% between consecutive photographs and 30% between transect lines, while in 2023 the target was 23% and 25%, respectively. The photographic reader examined both photographs of the overlapping area to detect narwhal presence. On some occasions where the detection of narwhal might have been uncertain, the reader may have used the complementary overlapping photograph to confirm the narwhal detection. Since readers can view narwhals in overlapping photographs to confirm sightings, the photographic survey should not be treated as instantaneous and the adjustment factor of availability bias should consider time-in-view (McLaren 1961, Laake et al. 1997). This information is important because overlapping photographs may introduce a positive bias depending on how the photographs are read; the photograph reader is more likely to identify a narwhal with certainty if the narwhal is located in two consecutive photographs. Therefore, this could result in an overestimate of narwhal abundance. For example, for an average narwhal dive cycle of 130 seconds, (with a surface time of 43 seconds and underwater time of 87 seconds (Asselin and Richard 2011, Doniol-Valcroze et al. 2020), and an interval of 6 sec between consecutive photographs, the difference between the instantaneous adjustment factor ($C_{instantaneous}$ = 3.02) and that considering time-in-view ($C_{6seconds}$ = 2.65) increases the abundance estimate by 14%. We recommend that the instantaneous adjustment be used for sightings in the non-overlap areas and that the time-in-view adjustment be used for sightings in the overlap areas.

In addition, for the 2023 survey, WSP (2024) provided a table with the difference in narwhal counts per photograph between two experienced photograph readers (Table 14). WSP (2024) retains the counts of the first reader which had higher overall counts than the secondary reader. This decision could introduce a positive bias in the abundance estimate; however, it is not possible to evaluate the magnitude of this bias because the original counts are not provided in the document. WSP (2024) states that 140 narwhal sightings were recorded during the August survey, comprising 353 individuals, resulting in mean and median group size of 2.5 and 2, respectively. However, numbers in Table 12 from WPS (2024) and information from the Executive Summary section indicate that the 140 narwhal sightings also include sightings made during the reconnaissance survey they conducted at the beginning of August. It is unclear if the mean group size used to calculate the abundance estimate also includes group size from the reconnaissance survey. This may introduce bias in the survey estimates, but more information about group size would be needed to evaluate the direction and magnitude of the bias.

Golder-WSP uses the same availability bias correction factor as in the 2013 High Arctic narwhal survey conducted by DFO (Doniol-Valcroze et al. 2015). However, it is recommended the availability bias correction factor be specific to each survey based on the best data available on narwhal diving behaviour and on the time available for an observer to see a group of narwhals (time in view). Ideally, these data should be collected during the same time period as the survey because narwhal diving is variable over time and is influenced by environmental factors (Heide-Jørgensen et al. 2001). Newer data on the narwhal dive cycle are available from satellite tagging studies in 2017-2018 (Golder Associates Ltd. 2019, 2020b) and should be matched in time with the survey to calculate an updated availability bias correction factor. The amount of time the ocean surface is in the observer’s view varies among surveys and depends on aircraft type and speed, and how the observer scans the ocean, which can vary between observers (Laake et al. 1997, Robertson et al. 2015). Therefore, time-in-view should be recorded as standard distance sampling practice (e.g., Richard et al. 2010, Pike et al. 2020). Based on our review of the Marine Mammal Observer Training Manual, presented in all Golder-WSP reports, it does not indicate that observers are recording the time in view of narwhals. Instead, they are only recording when a group of whales is abeam and not the time between the first sighting and abeam. However, it is possible to estimate the time in view based on the observers’ forward search angle and on the speed of the plane (Forcada et al. 2004, Gómez de Segura et al. 2006). This time in view could be incorporated into the availability bias estimate.

Golder-WSP's CVs on the survey estimates do not consider spatial autocorrelation in the uncertainty estimates for the adaptive photographic sampling (i.e., variance is calculated within each encounter based on differences among photographs, but without considering spatial relationships (Clegeur et al. 2021) or differences between photographic encounters). This has resulted in two components of variance being missed, and therefore a smaller than expected CV. It is not possible to determine this variance without access to the raw data. There is also uncertainty regarding the maximum depth that narwhal can be seen in a photograph or by observers, and this contributes to the variance. This was not considered by Golder-WSP, nor in the most recent surveys by DFO, but could be incorporated (NAMMCO-JCNB Joint Working Group 2021).

Abundance estimates

Some discrepancies in the reported abundances for some survey legs in Admiralty Inlet and Eclipse Sound have been identified. These discrepancies likely resulted primarily from rounding values and typographical errors in the reported narwhal densities or areas covered in the text. The discrepancies DFO Science identified usually resulted in negligible (< 0.03%) over- and underestimates of abundance. However, in 2021, they resulted in overestimates of 5% for some strata (see comments in Table 2). Values reported in Table 2 are the values indicated in the Golder-WSP reports.

Assessment

We calculated the yearly abundance estimate, $\widehat{N}$, by taking an average of the survey abundance estimates from each set of replicates for each year, weighted by effort. We adapted the methods proposed in Buckland et al. (2004, section 3.6.2); however, instead of averaging replicate transects, we averaged replicate complete surveys, similar to Gosselin et al. (2007). This approach of averaging complete surveys of the study area assumes that each survey covers the full extent of the stocks, but that the spatial distribution of individuals may change from replicate to replicate within a given year. Therefore, a different proportion of the stock may be distributed in each stratum of the survey. The adapted equation we used is:

$$\widehat{N} = \frac{\sum_{j=1}^{d} E_j \widehat{N}_j}{E_t}$$

Where E_j is the effort of each replicate, $\widehat{N}_j$ is the abundance estimate for each replicate, E_t is the total effort for all replicates, and d is the number of replicate surveys.

Rather than using the CVs reported in Golder Associates Ltd. (2020a, 2021, 2022) and WSP Canada Inc. (2023, 2024), which underestimate the uncertainty, we calculated the variance ($\mathrm{var}(\widehat{N})$) and associated CVs based on the total observed variation among survey replicates (adapted from equation 3.87 from Buckland et al. 2004, section 3.6.2).

$$var(\widehat{N}) = \frac{\sum_{j=1}^{d}[E_j(\widehat{N}_j - \widehat{N})^2]}{E_t(d-1)}$$

Combined estimates calculated this way are provided in Table 3. This approach yields larger CVs given the sources of uncertainty, except for the abundance estimate for Admiralty Inlet in 2022. In that instance, by calculating the CV of the two replicate surveys as described above, the CV is 5%, which is very low for a cetacean abundance estimate. This low CV results from the fact that the two replicate surveys estimated similar abundance (45,086 and 41,149; Table 2). Despite resulting in a smaller CV for this specific survey, DFO Science still recommends using the variation in abundance between replicate surveys, and that, in the future, a larger CV on the availability bias estimate be considered (such as that proposed in NAMMCO-JCNB Joint Working Group (2021)). Corresponding 95% confidence intervals (CI) around the abundance estimates were calculated based on the log-normal distribution (equation 3.71, Buckland et al. 2004; Table 3).

Most of the survey replicates that were discarded by Golder-WSP were not presented in their reports. However, survey 5 in 2019, survey 2 in 2022, and survey 3 in 2023 of the Eclipse Sound area were presented by Golder Associates Ltd. (2020a) and WSP Canada Inc. (2023, 2024), and have been included in our average estimates provided in Table 3. Generally, excluding data *a posteriori* can lead to reporting bias; a systematic decision framework to exclude survey data could be defined *a priori* (Neves and Amaral 2020).

Future Survey Recommendations

1. Use a systematic survey design and take photographs in conjunction with visual observations, as this provides validation of visual sightings (within the photographic coverage) and can be archived for future analyses.
2. Conduct repeat surveys and calculate average estimates across replicates to improve precision and reliability. Ensure that all survey replicates conducted under predetermined weather conditions are presented and analyzed. If a replicate is excluded from analysis, provide a clear and transparent justification, including criteria used to make the decision.
3. Update availability bias adjustment factors, 1) based on existing tag data from 2017-2018 that provide information on the full dive cycle, with an increased CV (Golder Associates Ltd. 2019, 2020b, Shuert et al. 2023), and 2) to account for environmental conditions such as water clarity (see above and Dogliotti et al. (2015), Watt et al. (2021), Lesage et al. (2024) for examples on measuring water clarity), bathymetry, etc.
4. Consider spatially explicit models for estimating abundance in full coverage photographic surveys to account for biases due to non-uniform survey coverage and spatially dependent data (i.e., overlapping imagery within and between transect lines, e.g., Cleguer et al. 2021).

CONCLUSIONS

The review detailed in this Science Response concluded the following:

1. Golder-WSP's survey design and methods primarily followed those developed and approved by DFO Science, and thus results from these surveys are appropriate for use in the current time series of abundance estimates for Admiralty Inlet and Eclipse Sound stock assessment modeling.
2. DFO Science identified some discrepancies in reported numbers, missing components of variance, as well as aspects of data collection and analysis that can be improved in future surveys. However, for existing surveys it was determined that these issues can be minimized by averaging the abundance estimates from the survey replicates (but see above for discussion regarding the 2022 Admiralty Inlet survey).
3. DFO Science recommends using the average abundance estimate of all relevant survey replicates presented by Golder-WSP for each year in Admiralty Inlet and Eclipse Sound (Table 3) for use in the current time series for Admiralty Inlet and Eclipse Sound stock assessment modeling.

4. Survey replicates that were not presented in the reports could not be evaluated and we recommend Golder-WSP provide all of the raw survey data.

Other Considerations

Narwhal abundance may be sensitive to the timing of the aerial surveys in relation to the sea-ice break up. Documenting changes in abundance in relation to sea-ice break up should be further explored.

DFO Science has recommended updating availability bias estimates, as the instantaneous estimates provided in Watt et al. (2015) are outdated and have an unrealistically small CV considering what we know about narwhal behaviour. It would be useful if DFO Science could provide detailed guidance on best practices for estimating instantaneous and non-instantaneous availability bias adjustment factors and consider methods to better capture uncertainty (e.g., increase the CV), such as those presented in NAMMCO-JCNB Joint Working Group (2021).

Table 2. Abundance estimates from Golder Associates Ltd. (2020, 2021, 2022) and WSP Canada Inc. (2023, 2024) for Eclipse Sound and Admiralty Inlet surveys. The surface estimates in the photographic surveys provided here have not been corrected for detectability bias. However, detectability and availability bias correction factors used to provide the final corrected estimate are indicated.

Year	Location	Survey	Date	Survey	Effort (km)	Surface estimate €	Detectability bias	Availability bias	Corrected Estimate¥	CV	95% CI
2019	Eclipse Sound	3	Aug 21–22	Visual	1,070.8	76	–	2.94	223	0.40	105–475
				Photo	373.5	1,973	1.20	3.18	7,542	0.04	6,983–8,145
				Combined	1,444.3	–	–	–	**7,765**	**0.04**	**7,182–8,396**
		4	Aug 25–27	Visual	1,036.5	518	–	2.92	1,514	0.59	522–4,390
				Photo	461.3	2,785	1.20	3.16	10,574	0.03	10,004–11,176
				Combined	1,497.8	–	–	–	**12,088**	**0.08**	**10,388–14,066**
		5	Aug 29–30	Visual	904.9[a]	373	–	2.92	1,090	0.25	667–1,781
				Photo	373.1	998	1.20	3.16	3,789	0.03	3,562–4,030
				Combined	1,278.0	–	–	–	**4,879**	**0.06**	**4,322–5,507**
	Admiralty Inlet	3	Aug 21–22	Visual	714.1	6,937	–	2.94	20,396	0.19	1,4134–2,9432
				Photo	168.7	1,857	1.20/1.17	3.18	7,040	0.03	6,697–7,400
				Combined	882.8	–	–	–	**27,436**	**0.14**	**20,860–36,084**
		4	Aug 25–27	Visual	516.8	6,821	–	2.92	19,918	0.44	8,727–45,459
				Photo	134.6	2,908	1.17	3.16	10,720	0.04	10,094–11,385
				Combined	651.4	–	–	–	**30,638**	**0.29**	**17,668–53,129**
		5	Aug 29–30	Visual	1,168.5	6,035	–	2.92	17,621	0.21	11,697–26,545
				Photo	15.4	357	1.20	3.16	1,355	0.04	1,250–1,468
				Combined	1,183.9	–	–	–	**18,976**	**0.20**	**12,963–27,779**
2020	Eclipse Sound	1	Aug 20–21	Visual	1,187.5	44	–	2.94	130	0.34	3,195–3,594
				Photo	371.7	960	1.11	3.18	3,389	0.03	68–247
				Combined	**1,559.2**	–	–	–	**3,519**	**0.03**	**3,308–3,743**
		2	Aug 24–25	-	1,5439.9	–	–	–	–	–	–
		3	Aug 28–29	Visual	1,177.3	62	–	2.92	181	0.39	4,588 – 5,099
				Photo	347.3	1,379	1.11	3.16	4,837	0.03	87 – 378
				Combined	**1,524.6**	–	–	–	**5,018**	**0.03**	**4,736–5,317**

Year	Location	Survey	Date	Survey	Effort (km)	Surface estimate €	Detectability bias	Availability bias	Corrected Estimate¥	CV	95% CI
		4	Aug 30–Sept 1	–	1,662.9	–	–	–	–	–	–
	Admiralty Inlet	1	Aug 20–21	Visual	1,231.0	4,907	–	2.94	14,427	0.22	9,425–22,084
				Photo	22.7	798	1.11	3.18	2,817	0.05	2,533–3,133
				Combined	**1,253.7**	–	–	–	**17,244**	**0.18**	**12,056–24,664**
		3	Aug 28–29	Visual	1,105.3	6,754	–	2.92	19,721	0.23	12,715–30,588
				Photo	166.1	3,223	1.11	3.16	11,305	0.03	10,677–11,970
				Combined	**1,271.4**	–	–	–	**31,026**	**0.14**	**23,406–41,126**
2021	Eclipse Sound	1-2	Aug 8–10	Visual	1,064.5	21	–	2.94	61	1	12–312
				Photo	361.4	605	1.10	3.18	2,111	0.04	1,989–2,241
				Combined	**1,425.9**	–	–	–	**2,172**	**0.04**	**2,005–2,353**
		4	Aug 19–21	Visual	1,210.3	297	–	2.94	873	0.99	172–4,429
				Photo	495.5	467	1.10	3.18	1,722[b]	0.05	1,594–1,860
				Combined	**1,705.8**	–	–	–	**2,595**	**0.33**	**1,369–4,919**
		5	Aug 26	Visual	1,195.7	7	–	2.92	20	0.96	4–98
				Photo	637.2	401	1.10	3.16	1,390	0.03	1,318–1,466
				Combined	**1,832.9**	–	–	–	**1,410**	**0.03**	**1,329–1,496**
	Admiralty Inlet	3	Aug 14–18	Visual	1,051.2	3,405	–	2.94	10,010	0.28	5,793–17,296
				Photo	88.6	4,024	1.10	3.18	14,037	0.04	12,935–15,233
				Combined	**1,139.8**	–	–	–	**24,047**	**0.12**	**18,989–30,452**
		4	Aug 19–21	Visual	1,141.8	4,435	–	2.94	13,038	0.43	5,765–29,485
				Photo	270.7	16,148	1.10	3.18	59,544[b]	0.04	54,626–64,904
				Combined	**1,412.5**	–	–	–	**72,582**	**0.09**	**61,333–85,895**
2022	Eclipse Sound	2	Aug 14–16	Visual	1,140.6	18	–	2.94	54	0.88	12–240
				Photo	374.8	251	1.17	3.18	936	0.03	879–997
				Combined	**1,515.4**	–	–	–	**990**	**0.06**	**885–1,107**
		3	Aug 17–18	Visual	1,190.8	6	–	2.94	18	1.11	3–104
				Photo	394.6	1,405	1.17	3.18	5,241	0.02	4,993–5,501
				Combined	**1,585.4**	–	–	–	**5,259**	**0.02**	**5,008–5,523**

Year	Location	Survey	Date	Survey	Effort (km)	Surface estimate €	Detectability bias	Availability bias	Corrected Estimate¥	CV	95% CI
		4	Aug 21	Visual	1,124.6	712	–	2.94	2,092	0.46	881–4,967
				Photo	369.0	478	1.17	3.18	1,782	0.04	1,656–1,918
				Combined	**1,493.6**	–	–	–	**3,874**	**0.25**	**2,387–6,287**
	Admiralty Inlet	2	Aug 14–16	Visual	1,147.0	13,463	–	2.94	39,581	0.29	22,502–69,623
				Photo	63.4	1,476	1.17	3.18	5,505 [d]	0.04	5,106–5,935
				Combined	**1,210.4**	–	–	–	**45,086**	**0.26**	**27,396–74,200**
		3	Aug 17–18	Visual	1,134.6	8,628	–	2.94	25,365	0.23	16,137–39,870
				Photo	240.9	4,232	1.17	3.18	15,784 [e]	0.04	14,868–16,756
				Combined	**1,375.5**	–	–	–	**41,149**	**0.14**	**31,038–54,554**
2023	Eclipse Sound	1	Aug 12-13	Visual	838.0	68	–	2.94	199	0.71	57–697
				Photo	451.8	3237	1.04	3.18	10,293	0.05	9,417–11,251
				Combined	**1,289.8**	–	–	–	**10,492**	**0.05**	**9,578–11,494**
		3	Aug 23-25	Visual	894.6	115	–	2.94	339	0.92	73–1,582
				Photo	484.5	2,903	1.04	3.18	9,233	0.04	8,588–9,926
				Combined	**1,379.1**	–	–	–	**9,572**	**0.05**	**8,706–10,524**
	Admiralty Inlet	2	Aug 19-20	Visual	842.8	7,950	–	2.94	23,372	0.19	16,068–33,996
				Photo	187.8	2,152	1.04	3.18	6,842	0.06	6,063–7,721
				Combined	**1,030.6**	–	–	–	**30,214**	**0.15**	**22,559–40,467**

€Surface abundance estimates were not provided by Golder-WSP for the visual aspect of their surveys. To calculate the surface abundance estimate we took the reported corrected abundance and divided by the availability bias correction. As a result, this surface abundance estimate already accounts for the detectability bias in the estimate.

*For the photographic surveys, the surface estimate is based on the density of whales on the surface in oblique photographs and does not yet include a detectability bias to account for variable detection across the photograph. Detectability bias varied across survey years and is reported above.

¥Corrected estimates for photographic surveys are those reported in Golder-WSP reports (2020a, 2021, 2022, 2023, 2024) and do not always sum to the surface abundance multiplied by the detectability and availability bias due to rounding.

[a]Golder Associates Ltd. (2020a) reported 944.9 in the text, but 904.9 in Table 11. We report and use (in Table 3) a surface abundance of 904.9 to remain consistent with the table presented in their report.

[b]Golder Associates Ltd. (2022) reported 467 (159 in Milne Inlet Sound and 308 in Tremblay Sound) narwhal as the surface non-adjusted abundance estimate; however, they note they multiply by detectability and availability bias estimates of 1.10 and 3.18, respectively. This results in a corrected abundance of 1,634, not

1,722 (586 in Milne Inlet South and 1,136 in Tremblay Sound), which they report and represents a 5% difference between the two estimates. However, we report and use (in Table 3) an estimate of 1,722 to remain consistent with their report.

[c]Golder Associates Ltd. (2022) reported 16,178 (2,923 in Admiralty Inlet North and 13,255 in Admiralty Inlet Sound) narwhal as the surface non-adjusted abundance estimate; however, they note they multiply by detectability and availability bias estimates of 1.10 and 3.18, respectively. This results in a corrected abundance of 56,591, not 59,544 (10,778 in Admiralty Inlet North and 48,766 in Admiralty Inlet South) that they report and represents a 5% difference between the two estimates. However, we report and used (in Table 3) an estimate of 59,544 to remain consistent with their report.

[d]WSP Canada Inc. (2023) reported 1,476 narwhal as the surface non-adjusted abundance estimate, but they note they multiply by detectability and availability bias estimates of 1.17 and 3.18. This results in a corrected abundance of 5,492, not 5,505 that they report. However, we report and used (in Table 3) an estimate of 5,505 to remain consistent with their report.

[e]WSP Canada Inc. (2023) reported an unadjusted surface abundance estimate of 4,232 narwhal, but they note they multiply by detectability and availability bias estimates of 1.17 and 3.18. This results in a corrected abundance of 15,746 not the 15,784 they report. However, we report and used (in Table 3) an estimate of 15,784 to remain consistent with their report.

Table 3. Abundance estimates derived from Golder Associates Ltd. (2020, 2021, 2022) and WSP Canada Inc. (2023, 2024) using all presented survey replicates and producing a weighted average (when possible) based on effort.

Year	Location	Survey	Date	Effort (km)	Estimate	CV	95% CI
2019	Eclipse Sound	3–5	Aug 21–30	4,220.1	8,425	0.25	5,221–13,596
	Admiralty Inlet	3–5	Aug 21–30	2,718.1	24,519	0.14	18,497–32,501
2020	Eclipse Sound	1 and 3	Aug 20–29	2,942.1	9,966	0.22	6,547–15,170
	Admiralty Inlet	1 and 3	Aug 20–29	2,525.1	24,183	0.28	13,986–41,816
2021	Eclipse Sound	1–2 and 4–5	Aug 8–26	4,964.6	2,036	0.18	1,445–2,868
	Admiralty Inlet	3–4	Aug 14–21	2,552.3	50,907	0.47	21,066–123,019
2022	Eclipse Sound	2–4	Aug 14–21	4,594.4	3,401	0.37	1,683–6,873
	Admiralty Inlet	2–3	Aug 14–18	2,585.9	42,992	0.05	39,311–47,018
2023	Eclipse Sound	1 and 3	Aug 10-25	2,668.9	10,017	0.05	9,155-10,959
	Admiralty Inlet	2	Aug 19-20	1,030.6	30,214	0.15	22,559-40,467

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