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Abundance Estimate of the South and East Hudson Bay Walrus (*Odobenus rosmarus rosmarus*) Stock from an Aerial Survey Flown in September 2022

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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.

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ABSTRACT

From September 1 to 13, 2022, an aerial photographic survey was flown to estimate the abundance of walruses from the South and East Hudson Bay (SEHB) stock. The entire SEHB range was covered. A total of 130 walruses were counted from aerial photographs within the survey area, 129 of which were from a single haul-out site on Kidney Island, and one individual on Eddy Island, in the Ottawa Islands archipelago. Correcting raw counts using the mean proportion of hauled out animals from the literature ($P = 0.3$, CV = 0.072) resulted in an abundance estimate of 432 (95% CI = 157–1188) animals. A second abundance estimate was calculated from 30 cm resolution satellite photographs of the main haul-out sites within the survey area, and that were obtained between August 11 and October 15, 2022. On satellite images, walrus aggregations were detected on Kidney Island, as well as on a small reef northwest of Cape Henrietta Maria. An average walrus aggregation density of 0.446 (CV = 0.027) individuals $\cdot$ m^{-2} was derived from georeferenced aerial photographs from Kidney Island collected during the 2022 survey. This density was multiplied by the area covered by walrus aggregations on satellite images to estimate abundance. This yielded uncorrected abundances of 61 and 129 walruses on Kidney Island and at a haul-out site near Cape Henrietta Maria, respectively. Adjusting these indices for the proportion of animals hauled out at the time satellite photographs were taken resulted in an abundance estimate of 633 (95% CI = 226–1770) individuals. Considering that the aerial survey and satellite imagery estimates were independent, a combined estimate of 494 (95% CI = 231–1054) walruses was derived for the SEHB stock. This abundance estimate is larger, but not significantly different, from the estimate produced by the last survey conducted in 2014 (i.e., 200 animals; 95% CI = 70–570). The potential biological removal (PBR) estimate for the SEHB stock was estimated at 4 animals per year.

INTRODUCTION

The Atlantic walrus ranges from the central Canadian Arctic eastward to the Kara Sea, in Russia (Born et al. 1995). Once widely distributed in Canada, including herds in cold temperate latitudes as far south as the Gulf of St. Lawrence and Sable Island (Scotian Shelf), Atlantic walruses were extirpated from southeastern Canada by the late 18th century (Reeves 1978; Born et al. 1995). Commercial hunting of walruses was banned in Canada in 1928, but walruses are still harvested by Inuit for subsistence throughout their range, with limited numbers being also taken in sport hunts (Stewart et al. 2014a; Matthews et al. 2018).

Walruses have narrow trophic and ecological niches. They depend upon rich feeding areas characterized by large extents of shallow water (≤ 80 m) supporting productive mollusk beds, a reliable access to open water during winter, and the presence of haul-out sites in close proximity to these feeding areas (Born et al. 1995). Walruses generally use ice pans as haul-out platforms during winter, and terrestrial sites during the ice-free summer and autumn periods (Davis et al. 1980). They are often found in aggregations.

In Canada, Atlantic walruses can be divided into High Arctic and Central/Low Arctic populations (COSEWIC 2017). Four largely distinct management stocks, based on genetics, distribution, telemetry, stable isotopes, and Traditional Ecological Knowledge, are identified within the Central/Low Arctic population, namely the Hudson Bay-Davis Strait (HBDS), Northern Foxe Basin, Central Fox Basin, and South and East Hudson Bay (SEHB) stocks (Stewart 2008; Shafer et al. 2014). The SEHB stock is distributed over an area of approximately 65,000 km^2, extending from the Ottawa Islands south to Ekwan Point in western James Bay (COSEWIC 2006; Figure 1). Separation of the SEHB from the HBDS stock is based on a gap in walrus distribution between Mansel Island and the Ottawa Islands, differential observations in local abundance trends between the two areas, and lead isotope ratios (Born et al. 1995; Outridge and Stewart 1999; Outridge et al. 2003).

There is virtually no information about historical population sizes or population trends for SEHB walruses (Born et al. 1995). The only comprehensive survey of the SEHB walrus stock was flown in September 2014, and walruses were detected on the Ottawa, Sleeper, Driftwood, and Belcher Islands. The 2014 survey yielded a stock size estimate of 200 (95% CI= 70–570) animals (Hammill et al. 2016). Prior to this survey, the only proxies of abundance for SEHB walruses were counts reported from individual haul-out sites by a variety of sources (COSEWIC 2006). While > 400 animals were reported in the northern Sleeper Islands in the late 1930s (Twomey and Herrick 1942), more recent sightings report substantially smaller herds for eastern Hudson Bay (e.g., 25 – 75 walruses in the Sleeper Islands area, and ~30 walruses in the Belcher Islands between the 1970’s and late 1990’s; COSEWIC 2006). Nevertheless, 310 walruses were counted on photographs taken during a goose survey at Cape Henrietta Maria in 1978 (Born et al. 1995). Although there are insufficient data to assess whether there has been a decline in the SEHB stock, hunters from Sanikiluaq report that they now see fewer walruses in the Belcher Islands area than they did in the past (DFO 2000).

Under the precautionary approach (DFO 2006), SEHB walruses are considered data poor. Accordingly, DFO has adopted the Potential Biological Removal (PBR) approach to estimate sustainable removals, and provide periodic harvest advice for the different walrus stocks (Stewart and Hamilton 2013; DFO 2016ab, 2023). The PBR is a tool for quantifying the maximum annual number of animals that may be removed from a stock by all means other than natural mortality, that would allow the population to have a 95% probability of being above the Maximum Net Productivity Level (i.e., 50% of the carrying capacity) in 100 years (Wade 1998).

This study presents results from a coastal photographic aerial survey targeting haul-out areas, and flown in September 2022, to estimate abundance of the SEHB walrus stock. In addition, satellite images covering most known haul-out sites within the SEHB distribution range were obtained to generate an independent abundance estimate for the stock. Results from both approaches were combined to provide an overall abundance estimate. Total allowable removals are estimated using the PBR approach.

METHODS

SURVEY AREA AND PROTOCOL

The survey area included the entire SEHB walrus stock distribution range (Figure 1). A list of known walrus haul-out sites was obtained from community consultations conducted in preparation for the previous 2014 survey (Hammill et al. 2016), a literature review of reported sightings, and observations reported by communities to Uumajuit Wardens. A map of haul-out sites to be targeted was shared prior to the 2022 survey with the regional and local Nunavimmi Umajulirijiit Katujiqatigininga (RNUK and LNUK; hunters organizations), Uumajuit Wardens, and the Nunavik Marine Region Wildlife board (NMRWB) to get feedback and ensure the list included all known walrus haul-out locations within the study area. Survey track lines were planned to fly over all identified sites (Figure 2). To account for the possibility that animals may haul out outside of the traditional sites, flights were also conducted over surrounding islands or coastal areas between sites.

The aerial survey was designed to be flown in September 2022, at a target altitude and speed of 1,000 feet (305 m) and 100 knots (185 km/h), respectively, using a deHavilland Twin Otter 300 aircraft. The survey crew consisted of two trained marine mammal observers stationed on each side of the aircraft looking through bubble windows located at the second seat row. Additional observers, when available, sat primarily in the left, last row seat which was also equipped with a bubble window. Observers were able to see directly under the aircraft, and were instructed to observe the area in their field of view, including open water and the shoreline while the plane followed the coastline. When marine mammals were visually detected, the observer recorded the time of each sighting for later georeferencing, as well as the species and number of animals detected.

The aircraft was equipped with a large belly port in the rear, allowing the collection of photographic images directly below the aircraft. The camera system comprised two digital cameras (Nikon D-800 with a Zeiss 35 mm lens) mounted on a custom frame, and aimed to the right and left of the plane at an angle of 27.2º from the nadir. The cameras were oriented widthwise (long side perpendicular to the track line), resulting in an image swath of 425 m on each side of the aircraft. The flight path was continually adjusted to ensure the coastline remained within the cameras' field of view. Each camera was controlled by a laptop computer using the Nikon Camera Control Pro 2 software and set to take one image every 3 seconds, resulting in an overlap of ~37% between successive photos. The main observer sitting on the offshore side of the aircraft acted as navigator/camera operator during the flights.

The location and altitude of the aircraft were recorded every second using GPS devices (Garmin GPSMap78 and Bad Elf GPS pro). The camera times were synchronised with GPS time, and images were georeferenced *post hoc* by linking images and GPS locations based on time.

AERIAL PHOTO ANALYSIS

Owing to the large number of images taken during the survey, a triage approach was used to select photographs to be examined for walruses. First, walruses were counted in photographs taken at times when observers had reported seeing animals. Next, photographs taken at previously known haul-out sites were examined even if no walrus observation was recorded during the survey. Starting with the photographs taken either at the time of the observation or of arrival at the haul-out site, readers counted every walrus visible on that image as well as on the previous and next 10 photos taken from both sides of the plane. If a walrus was detected in one of these previous or next 10 images, then the previous and next 10 photographs were checked, and so on, until no new walruses were detected. The rest of the photographs from other islands and reefs were subsampled following an adapted cluster sampling procedure: 65 series of 20 photographs (corresponding to 10% of on-effort photographs) were randomly chosen among those left unread. When animals were identified in a series, the previous and next 10 photos from both sides of the plane were examined, until animals were no longer identified in 10 consecutive photos. Photographs on which walruses were identified were counted at least twice by different readers, and the highest count was retained. If counts differed by more than 3%, the image was re-examined by a third observer to obtain a consensus count.

Images displaying walrus aggregations were georeferenced to estimate walrus density in these aggregations. The number of animals occurring in each haul-out aggregation was divided by the area occupied by the walruses, defined as a polygon drawn in QGIS around the aggregation. Walruses in the water on pictures were excluded from aggregation polygons. The average density was later used in the satellite imagery analysis (see below).

SATELLITE IMAGERY

WorldView-3, WorldView-2, and GeoEye satellite constellations were tasked via Maxar Technologies to collect images of multiple areas encompassing most of the known walrus haul-out sites in the SEHB distribution area during September 2022, i.e., as close as possible to the aerial survey window (Figure 3). Pansharpened, 30-cm resolution, orthorectified images were obtained.

The georeferenced satellite images were processed in QGIS 3.22.0 or 3.32.0 (QGIS Development Team 2023) and visually assessed at a scale ranging between 1:540 and 1:1000, depending on soil color and contrast. Image enhancement included manipulating brightness, contrast, and saturation, as well as varying the contributions of the four color band components to optimize walrus detection. The 30-cm resolution of the satellite images was sufficient to detect walrus aggregations, but insufficient to reliably count individual walruses aggregated at haul-out sites (Matthews et al. 2022). Instead, when aggregations of walruses were detected on satellite images, the number of animals hauled out was estimated by multiplying the area (polygon drawn in QGIS) occupied by walruses by the average walrus density derived from the aerial survey images (see above). Walrus aggregation contours were drawn on satellite images by at least two different readers, and the polygon with the largest area was retained. If resulting walrus numbers differed by more than 3%, the aggregation contour was redrawn by a third observer.

COUNT ANALYSIS

Poor weather conditions prevented us from flying every day. Little is known about walrus movements in the area, but animals could move between sites during the survey, potentially resulting in some individuals being counted twice or missed. Information about site fidelity and walrus movements in Canadian waters, particularly potential movements between haul-out sites, is lacking. We considered that animals were able to move randomly between haul-out sites, and counts conducted at the same site but separated by more than 24 hours were considered independent. Multiple counts resulting from the repositioning of the aircraft to ensure optimal coverage of a haul-out site were not considered independent, and the highest count (i.e., from pictures displaying the maximal extent of the walrus aggregation, and the minimal number of walruses flushed in the water due to disturbance by the aircraft) was kept in those cases.

Some animals present on the haul-out sites may have been missed. The latter point was considered negligible for the aerial survey, as counts were obtained from photographs and detection probability was considered equal to 1 (Stewart et al. 2014c; Hammill et al. 2016; Mosnier et al. 2023).

The proportion of the total population occurring at haul-out sites at the time of the survey is unknown (Stewart et al. 2013, 2014bc). Different methods have been used to derive total walrus abundance from haul-out counts and the adjustment factors to account for animals missed because they were at sea (Johnson et al. 2007; Stewart and Hamilton 2013; Stewart et al. 2014c). Simulations using virtual populations indicated that the simple count (SC) method provides a reliable and unbiased estimator of abundance (Doniol-Valcroze et al. 2016). This SC methods uses the total number of hauled out animals, or the mean of counts when an area is repeatedly surveyed. Accordingly, counts from haul-out sites separated by more than 24 h were considered independent, and were averaged. The abundance estimate at each haul-out site *i*, $\widehat{N_\imath}$, was then calculated as:

$$\widehat{N_\imath} = \frac{C_{mean_i}}{P} \qquad \text{(equation 1)}$$

where *P* = 0.30 (CV = 0.072), the average of published values of the proportion of animals hauled out for Atlantic walrus stocks (Table 2 in Hammill et al. 2016) and C_{mean_i} is the mean number of walruses recorded at site *i*. The variance of $\widehat{N_\imath}$ was calculated as:

$$var\left(\widehat{N_\imath}\right) = \left[\widehat{N_\imath} \times \frac{1-P}{k \cdot P} \times \sigma^2\right] + \left[\widehat{N_\imath^2} \times \frac{var(\hat{P})}{\widehat{P^2}}\right] \text{(equation 2)}$$

Where the first term accounts for the variation in counts, while the second term represents the variation associated with the proportion hauled out. In equation 2, *k* is the number of independent counts, and σ^2 is an overdispersion factor defined as:

$$\sigma^2 = 1 + \left(\widehat{N_\imath} - 1\right) \times \rho \text{ (equation 3)}$$

where ρ (the correlation factor among walruses) = 0.26 (95% CI = 0.140–0.362; Mosnier et al. 2023) based on a Bayesian model applied to the framework developed by Doniol-Valcroze et al. (2016). The population abundance estimate ($\hat{N}$) and its variance were calculated as:

$$\hat{N} = \textstyle\sum_{n}^{i=1} \hat{N}_i \text{ (equation 4)}$$

$$var(\hat{N}) = \textstyle\sum_{n}^{i=1} var(\hat{N}_i) \text{ (equation 5)}$$

Confidence limits were estimated assuming a lognormal distribution around $\hat{N}$. Considering that the aerial survey ($\widehat{N_a}$) and the satellite imagery ($\widehat{N_s}$) estimates represent two independent estimates of abundance, the latter can be combined ($\widehat{N_C}$), inversely weighted by their variances $var(\widehat{N_a})$ and $var(\widehat{N_s})$, respectively, using:

$$\widehat{N_C} = \frac{[(\hat{N}_a \cdot var(\widehat{N_s})) + (\widehat{N_s} \cdot var(\widehat{N_a}))]}{var(\widehat{N_a}) + var(\widehat{N_s})} \qquad \text{(equation 6)}$$

with its error variance calculated as:

$$var(\widehat{N_C}) = \frac{var(\widehat{N_a}) \cdot var(\widehat{N_s})}{var(\widehat{N_a}) + var(\widehat{N_s})} \qquad \text{(equation 7)}$$

POTENTIAL BIOLOGICAL REMOVAL

The PBR is calculated as:

$$PBR = 0.5\, R_{max} \times RF \times N_{min} \qquad \text{(equation 8)}$$

Where R_{max} is the maximum rate of population increase, *RF* is a recovery factor ranging between 0.1 and 1, and N_{min} is the estimated population size using the 20th percentile of the assumed log-normal distribution around the abundance estimate (Wade 1998). Recovery factor values < 1 allocate a proportion of the expected net production to demographic growth, while accounting for uncertainties hindering population recovery (National Marine Mammals Service 2016). For consistency with most recent walrus assessments (U.S. Fish and Wildlife Service 2013; Hammill et al. 2023), R_{max} was set to a default of 0.08. Based on the guidelines for application of *RF* in Canada (DFO 2018), the *RF* was set to 0.25 as indicated for small populations with a stable trend. The N_{min} was calculated as:

$$N_{min} = \frac{\widehat{N_C}}{\exp\left(z\sqrt{\ln\left(1+CV(\widehat{N_C})^2\right)}\right)} \qquad \text{(equation 9)}$$

Where $\widehat{N_C}$ is the most recent population size estimate, *z* is the standard normal variate (0.824 for the 20th percentile), and $CV(\widehat{N_C})$ is the coefficient of variation for $\widehat{N_C}$.

RESULTS

A total of 25 haul-out sites were identified in the planned survey area, of which 23 were surveyed at least once during September 1-13, 2022 (Table 1). The two sites not surveyed represented point locations provided from walrus sighting data that turned out to be in open water, with no substrate for walruses to haul out on. Therefore, this survey covered all of the potential walrus haul-out sites identified in southeastern Hudson Bay, as well as other islands, reefs, and rocky coasts representing potential suitable habitat.

The survey was completed within 6 flying days over this 13-day period, for a total of 42 hours of flight. A total of 49,065 aerial photographs were recorded, of which 10,480 were examined for walruses. Walruses were detected by observers at two different locations during the survey (Figure 4). One single walrus was identified both visually and on images on a small island east of Eddy Island, in the Ottawa Islands. A small aggregation of walruses was also detected both visually and on aerial photographs on the southern portion of Kidney Island. This haul-out site was surveyed on two dates, and flown twice on both dates (Table 1). Only the largest count from each date was retained. Aerial images (Figure 5) yielded total counts for this site of 126 and 131 individuals on September 5 and 10, respectively. Numbers estimated visually by observers when flying over the haul-out (105 and 50 on September 5 and 10, respectively) were consistently lower than counts from corresponding aerial photographs, therefore counts from photographs were retained. No additional walruses were detected by observers in the plane, upon examination of aerial images from all other reported haul-out sites, or on aerial images randomly chosen. Based on aerial photographs, the number of walruses counted on haul-out sites within the SEHB distribution area was estimated at 130 walruses. Correcting this index to account for animals at sea resulted in an estimate of 432 (CV= 0.553, 95% CI= 157–1188) walruses.

The September 5 and 10 passes over the aggregation yielded walrus densities on the photographs of 0.436 and 0.453 individuals·m^{-2}, respectively, corresponding to an average walrus density of 0.446 (CV= 0.027) individuals·m^{-2} which was used to estimate the number of walruses hauled out visible on the satellite images.

A total of 544 satellite images were examined for walruses. Cloud-free satellite images of the entire SEHB stock distribution range could not be obtained within the exact dates of the aerial survey, thus the period covered by the satellite imagery extended from August 11 to October 15, 2022 (see Table 1 for temporal distribution of satellite imagery coverage of the targeted haul-out sites). Aggregations of hauled out walruses were identified at three locations: the same haul-out site on Kidney Island where walruses were detected during the aerial survey (Figure 6A), a second haul-out site on Kidney Island located approximately 180 m south of the first one, and a haul-out site northwest of Cape Henrietta Maria (Figure 6B) that was covered during the aerial survey, where no walruses were detected (Figure 4). Based on the mean density estimate from aerial photographs, the number of walruses hauled out on Kidney Island was estimated at 66 and 55 walruses on August 16 and September 6, respectively. An additional estimate of 129 walruses were hauled out northwest of Cape Henrietta Maria on September 18 (Table 2). Correcting the estimated number of walruses hauled out on the images to account for animals at sea resulted in an estimate of 202 (CV= 0.559, 95% CI= 73–561) walruses on Kidney Island, and 431 (CV= 0.784, 95% CI= 111–1674) walruses near Cape Henrietta Maria. The Kidney Island and Cape Henrietta Maria detections were separated by ~290 km, making it unlikely that animals moved between the two sites within the eight days separating satellite image collection and the survey flown over Kidney Island on September 10. Combining the two sites resulted in a total estimate of 633 (CV=0.562, 95% CI=226–1770) walruses for the SEHB stock based on satellite imagery.

The combined estimate of abundance using data from both the aerial survey and satellite images was 494 (CV= 0.399, 95% CI=231–1054) walruses.

The PBR was estimated at 3 walruses per year based on the 2022 aerial survey estimate (Table 3), and at 4 walruses per year using the walrus abundance estimate derived from satellite imagery. If the two independent estimates are combined, then the PBR is 4 walruses per year (Table 3).

DISCUSSION

Estimating walrus abundance is particularly challenging owing to their typically clumped distribution, the uncertainty in the proportion of animals hauled out, and the unknown rates of movement between haul-out sites (Mosnier et al; 2023; Mansfield and St. Aubin 1991, Lydersen et al. 2008, Stewart et al. 2014b, Doniol-Valcroze et al. 2016). This is reflected in the high level of uncertainty associated with abundance estimates from walrus surveys (Doniol-Valcroze et al. 2016). In this survey, we obtained an abundance estimate of 494 (95% CI= 231–1054) walruses. The only previous survey of the SEHB was flown in September 2014, and yielded an abundance estimate of 200 (95% CI= 70–570) animals using the SC method, which was also used to estimate abundance in the present study. The abundance estimate from the 2022 survey is higher, but not significantly different from that of the previous survey. While additional surveys are required before a demographic model can be fit for the SEHB walrus stock, both the 2014 and 2022 assessments indicate that the stock abundance is low.

Because difficult weather conditions in the Arctic typically limit the number of suitable flying days, if would be particularly challenging to further constrain survey conditions to additional factors such as tide levels, as is done in some pinniped species (e.g., Hamilton et al. 2023; Lidgard et al. 2023; Mosnier et al. 2023). As a result, a logistical limitation to this study is that some identified haul-out sites might have been partially or completely submerged when the survey was flown. While this may lead to some walruses being at sea and thus not counted during the survey, the proportion hauled out used to correct for animals at sea was calculated across tide levels, and is therefore considered to adequately account for this. However, the clumped distribution of walruses, which is partly attributable to tide levels, is responsible for most of the variance associated with abundance estimates. Flying surveys at low tides might improve survey estimates and facilitate trend detection in the time series by decreasing the haul-out correlation factor among walruses that is used in the calculation of variance, thus narrowing confidence intervals around abundance estimates.

During the 2014 survey, walruses were detected on Ottawa, Sleeper, Driftwood, and Belcher Islands, while only one walrus aggregation located on the southern portion of Kidney Island was detected during the 2022 survey. Interestingly, the walrus aggregation detected during this survey was also identified during the last eastern Hudson Bay beluga aerial survey flown in the area in August 2021 (DFO, unpubl. data). Although the 2021 beluga stock assessment was a visual survey, opportunistic photographs were taken from the plane at this walrus aggregation. A total of 134 walruses were counted from these photographs, which is very similar to the uncorrected counts (126 and 131) obtained for this haul-out site during the 2022 walrus photographic survey. Little is known about daily and inter-annual walrus movements between haul-out sites. Telemetry data from one adult male from NE Greenland tracked over four summer seasons showed strong philopatry to a single terrestrial haul-out site (Born et al. 2005). In contrast, telemetry data from male walruses tagged in Svalbard indicated that individuals tagged together displayed synchronicity in their haul-out behaviour during summer, but did not necessarily haul out at the same place (Lydersen et al. 2008). Because aerial surveys represent a snap-shot of distribution, it is not possible to determine whether the differences in the haul-out sites used by walruses detected during the 2014 and present surveys resulted from a spatial displacement of walruses over the years.

Matthews et al. (2022) demonstrated that walruses could be visually detected from 30-cm resolution satellite imagery, and that measuring the surface areas of walrus aggregation could yield reasonable estimates of animals hauled out when multiplied by densities derived from archived aerial survey photographs. A density estimate of 0.446 (CV= 0.027) individuals·$m^{-2}$was obtained from photographs of animals hauled out at Kidney Island. The number of photographs with walruses on them that were available for density estimation from the 2022 aerial survey is low (N = 2). As a result, the uncertainty around this estimate is likely underestimated since both pictures are from the same haul-out site, and were captured in similar weather conditions. Similarly, repeated counts of two aerial photographs from a single flyover of a haul-out site on Ellesmere Island, Nunavut, yielded an average density of 0.62 (CV = 0.008) individuals·m^{-2} (Sherbo et al. 2023). In contrast, Matthews et al. (2022) calculated a mean density of 0.941 (CV= 0.245) individuals·m^{-2} from photographs of various parts of Walrus Island, in northern Hudson Bay, highlighting that walrus density can vary considerably between haul-out sites. Given the large variability in the haul-out behaviour of walruses, differences in walrus densities between hauled out aggregations from different areas may reflect temporal variability in haul-out behaviour (Fischbach et al. 2021), inter-regional differences in haul-out densities, an artifact of topography, or may simply be a reflection of a very small sample size. Given the small CV value around the mean aggregation density estimate for Kidney Island, its contribution to the variance around the abundance estimate was deemed negligeable, thus the density was introduced without its error term in the calculation of abundance from satellite imagery. The methodology used in the present as well as previous studies (Matthews et al. 2022; Sherbo et al. 2023) assumes a uniform walrus density within aggregations. Given the small size (25-291 m^2) of walrus aggregation areas observed in this study, this assumption is likely valid. Factors affecting suitable substrate availability and walrus haul-out behaviour (e.g., tide levels, sea state conditions, stock abundance) on local walrus densities should nevertheless be considered in further studies, which requires obtaining larger numbers of images under different conditions. Ground-based time-lapse photographs of haul-out sites would help to address this question.

The southern Kidney Island haul-out site is the only one where walruses were detected both from aerial and satellite imagery, allowing for comparison between counts obtained from the two methods. The aerial survey photographs and satellite images yielded abundance estimates for this haul-out site of 428 (95% CI= 155–1187) and 202 (95% CI= 73–561) walruses, respectively. These numbers do not differ significantly, and are within the expected range of variation for hauled out walrus numbers on a given haul-out site (Mansfield and St-Aubin 1991). However, a potential explanation for the somewhat lower number of walruses estimated from satellite photographs compared with aerial photographs might be that animals were disturbed by the approaching aircraft, resulting in some walruses entering the water by the time the aircraft was directly overhead and photographing the haul-out site (e.g., see Figure 5A). A second or third flyover was occasionally necessary to clearly capture walruses on photos, increasing the proportion of animals in water. As was done in previous walrus aerial surveys (Mosnier et al. 2023; Hammill et al. 2016), walruses in the water and visible on photographs next to the haul-out were assumed to have been hauled out and were included in the aerial survey counts. Some animals may have departed the site, leading to negative bias, whereas counting all the animals in the water immediately around the haul-out may also have included some animals that had already been in the water in the survey counts, which would introduce a positive bias in abundance estimates because counts were adjusted by the proportion of animals assumed to be hauled out (0.30). However, walruses in the water were not included in the aggregation polygons used to estimate walrus density from the satellite imagery. Using aerial photographs on which walrus haul-out distribution has been disturbed by the plane may induce a negative bias in the walrus haul-out density used to derive abundance from satellite images. Flight trials to identify altitudes at which aircrafts cause minimal disturbance while balancing the needs to acquire photographs of suitable resolution to discern individual walruses should be attempted in preparation for future surveys.

A walrus aggregation was detected on satellite images off Cape Henrietta Maria, but no walruses were observed on aerial photographs from the same area. This is likely due to the site being underwater when the survey aircraft passed overhead at a higher tide level than when the satellite images were taken. On Kidney Island, a minimum of 66 walruses were detected on satellite imagery taken on September 6, and 131 animals were photographed hauled out during the aerial survey on September 10. The aggregation at Cape Henrietta Maria was detected on satellite images taken on September 18. For the Kidney Island aggregation to have moved to Cape Henrietta Maria, animals would have had to undertake a synchronous, directed movement covering an average of 36 km·day^{-1}. This is lower than the daily movement cutoff of 45 km·day^{-1} used to minimize the probability that animals may have been counted twice in previous aerial walrus surveys of the Hudson Bay-Davis Strait and SEHB stocks (Stewart et al. 2014b; Hammill et al. 2016). It Is also lower than the average daily travel distances calculated from walruses tagged with GPS telemetry devices in the Pechora Sea (northwest Russia), Svalbard, Greenland and Faroe, which ranged between 66 and 120 km·day^{-1} (median from these studies: 82 km·day^{-1}; Lydersen et al. 2008; Born et al. 2005, 2014; Semenova et al. 2019). Therefore, it is possible that walruses moved between haul-out sites during the interval between image collection. However, it seems unlikely that the entire herd would have undertaken a continuous, directional movement between the haul-out sites over these eight days. Therefore, walruses located on the satellite imagery near Cape Henrietta Maria were considered to represent a separate group and added to the counts from the satellite imagery estimate.

Combining the overall abundance estimates obtained from the aerial survey (432; 95% CI= 157–1188) and satellite imagery (633; 95% CI= 226–1770) resulted in a total abundance estimate of 494 (95% CI= 231–1054), and reduced the uncertainty around the stock abundance estimate. This combination assumes the aerial survey and satellite imagery yielded independent abundance estimates. However, this assumption might not be fully respected, as photographs from the aerial survey were used to estimate walrus aggregation density applied to derive abundance from satellite images. Nevertheless, averaging abundances derived from both methods was deemed appropriate because aerial and satellite images were collected at different dates.

Satellite imagery is increasingly used to study abundance and distribution of large-bodied animals (e.g., baleen whales, Fretwell et al. 2014, Cubaynes et al. 2018; polar bears, *Ursus maritimus*, Stapleton et al. 2014, LaRue and Stapleton 2018) and species that have body colouration that contrasts highly with that of their substrate (e.g., albatrosses, *Diomedea exulans* and *sanfordi*, Fretwell et al. 2017; whooper swans, *Cygnus cygnus*, Zhao et al. 2020; Weddell seals, *Leptonychotes weddellii*, Ainley et al. 2015; elephant seals, *Mirounga leonina,* McMahon et al. 2014). Satellite imagery offers some advantages compared to aerial surveys: satellites cover large geographic areas, including remote sites which are difficult to access; they can cover a same site repeatedly over a short period of time, potentially providing replicated spatial coverage within a short interval; and the method is completely non-invasive to animals that are prone to disturbance from low-flying aircraft (Matthews et al. 2022). However, the resolution of commercially available satellite images does not yet rival that of images obtained during aerial surveys, thus the method still heavily relies on aerial photographs to derive site-specific walrus densities on haul-out sites. In addition, cloud-free satellite images of the entire SEHB stock distribution range could not be obtained within the exact dates of the aerial survey (September 1-13, 2022), thus the period covered by the satellite imagery extended over a 2-month period (August 11 to October 15, 2022). Estimating total stock abundance from haul-out sites photographed at longer time intervals challenges the assumption that animals display no directional movement between sites during the study period. Moreover, it was not possible to obtain replicate images for all identified haul-out sites. As reported in other studies, obtaining cloud-free satellite images in the Arctic region during the open-water season characterized by frequent fog and cloud cover is challenging (e.g., Matthews et al. 2022; LaRue and Stapleton 2018). Finally, commercially-available satellite imagery remains costly. The cost for the purchase of satellite images and the time required to analyze these images was estimated at 70% of the cost of the aerial survey completion and aerial photograph analysis. If satellite images could have been collected and analyzed for the entire set of haul-out sites covered during the aerial survey (Figure 1 versus Figure 2), the satellite imagery and aerial survey would have had similar costs.

The aerial survey covered the entire study area within a 13-day period, including replicated passes over areas where walruses were detected by observers. The relatively low target flight altitude (305 m) relaxed the constraints on cloud coverage compared with satellite imagery. The high resolution images collected during the survey yielded walrus counts and density for individual haul-out sites which are required to derive abundance from satellite imagery. Therefore, for the moment, aerial photography and satellite imagery survey can been seen as complementary abundance estimation methods. Their combination provided replicated surveys of haul-out sites, which is necessary to capture the high variability in walrus numbers observed at haul-out sites over short time periods (Mansfield and St-Aubin 1991).

The PBR for the SEHB walrus stock, estimated from the combined aerial survey and satellite imagery abundance estimates, is 4 animals per year. Reported harvest from this stock has decreased over the last decades due to an increase in detection of *Trichinella* in harvested animals (Hammill et al. 2016), and averaged 3 (SE= 0.9) animals per year over the last 10 years (Table 4). The *RF* value used in this assessment was based on available guidelines for application of *RF* levels for use in Canada (DFO 2018), which indicate that the PBR for small populations with increasing or stable trends should be calculated using an *RF* = 0.25. However, these guidelines are evasive and open to interpretation (e.g., they provide no indication on the timeframe to consider to describe the population trend). Revisiting these guidelines and providing clarifications and practical examples would promote more consistent PBR calculation for marine mammal stocks in Canada.

In this assessment we provided an estimate of abundance for the SEHB walrus stock based on the combination of an aerial photographic survey and satellite imagery. There are several uncertainties associated with this study, including the need to improve our understanding of walrus movements between haul-out sites, and of haul-out behaviour. The latter probably has the most significant impact on the proportion of animals hauled out during the survey period (availability bias), as well as on the uncertainty associated with this haul-out proportion (Doniol-Valcroze et al. 2016). Ideally, satellite transmitters would be deployed on animals during the survey to obtain a stock- and year-specific estimation of the proportion of animals hauled out during the survey period that can be used to correct counts for animals that are in the water. Transmitters were not deployed during this survey, and estimates of the proportion of animals hauled out was inferred from other studies, as was the case for the last assessment of the SEHB stock (Hammill et al. 2016). The SEHB stock structure and distribution is poorly understood. Walruses once extended into James Bay, and an aggregation was detected at Cape Henrietta Maria from satellite imagery in this study. However, no genetic analysis has been performed on walruses from this stock, therefore it is unclear if they form a unique stock, or represent the southern limits of the Hudson Bay-Davis Strait stock. Identifying the genetic relatedness of walruses found within the SEHB stock distribution area would improve our understanding of walrus stock structure in the Central/Low Arctic population. If SEHB and HBDS walruses form a single stock, PBR would need to be recalculated based on total stock abundance.

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FIGURES

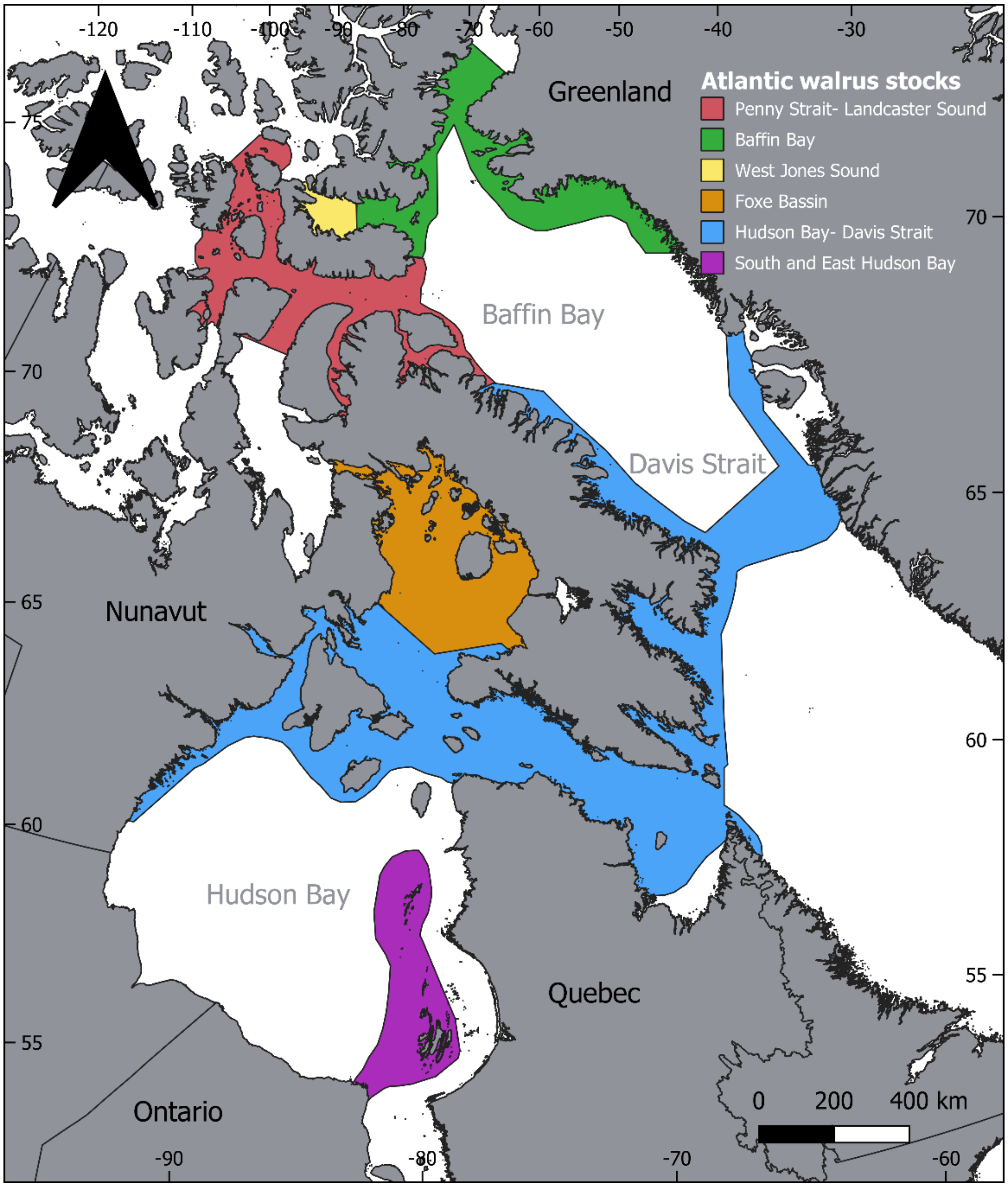

Figure 1. Distribution range of Atlantic walrus stocks in the eastern Canadian Arctic. Modified from Hammill et al. 2016. The current survey aimed to estimate abundance for the South and East Hudson Bay stock (purple polygon). Latitude and longitude in degrees are indicated along the x- and y-axes.

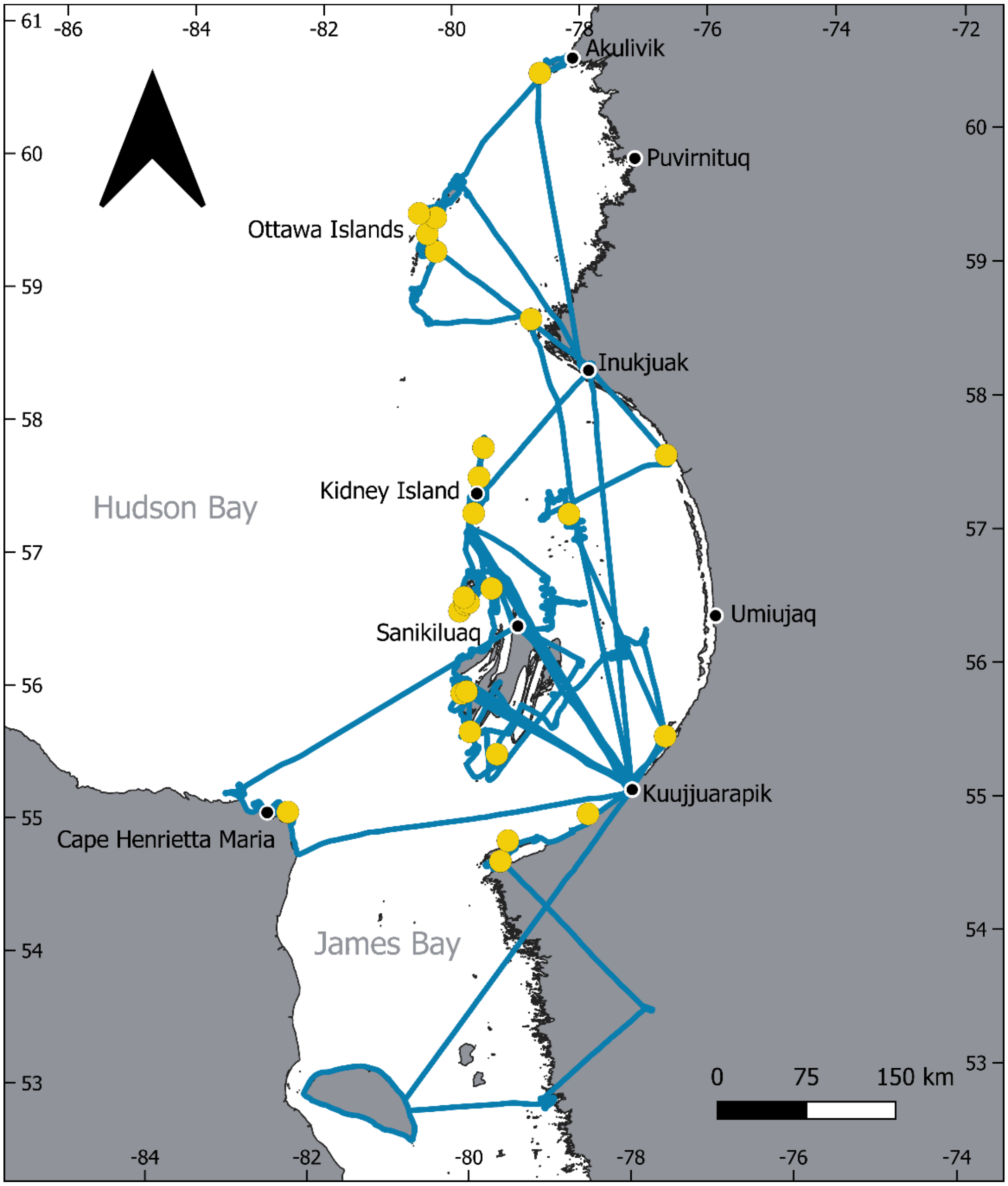

Figure 2. Locations of known walrus haul-out sites (yellow circles) from previous surveys, discussion with Inuit hunters, and historical reports, along with survey tracks (blue lines) flown by the aircraft during September 2022. Latitude and longitude in degrees are indicated along the x- and y-axes.

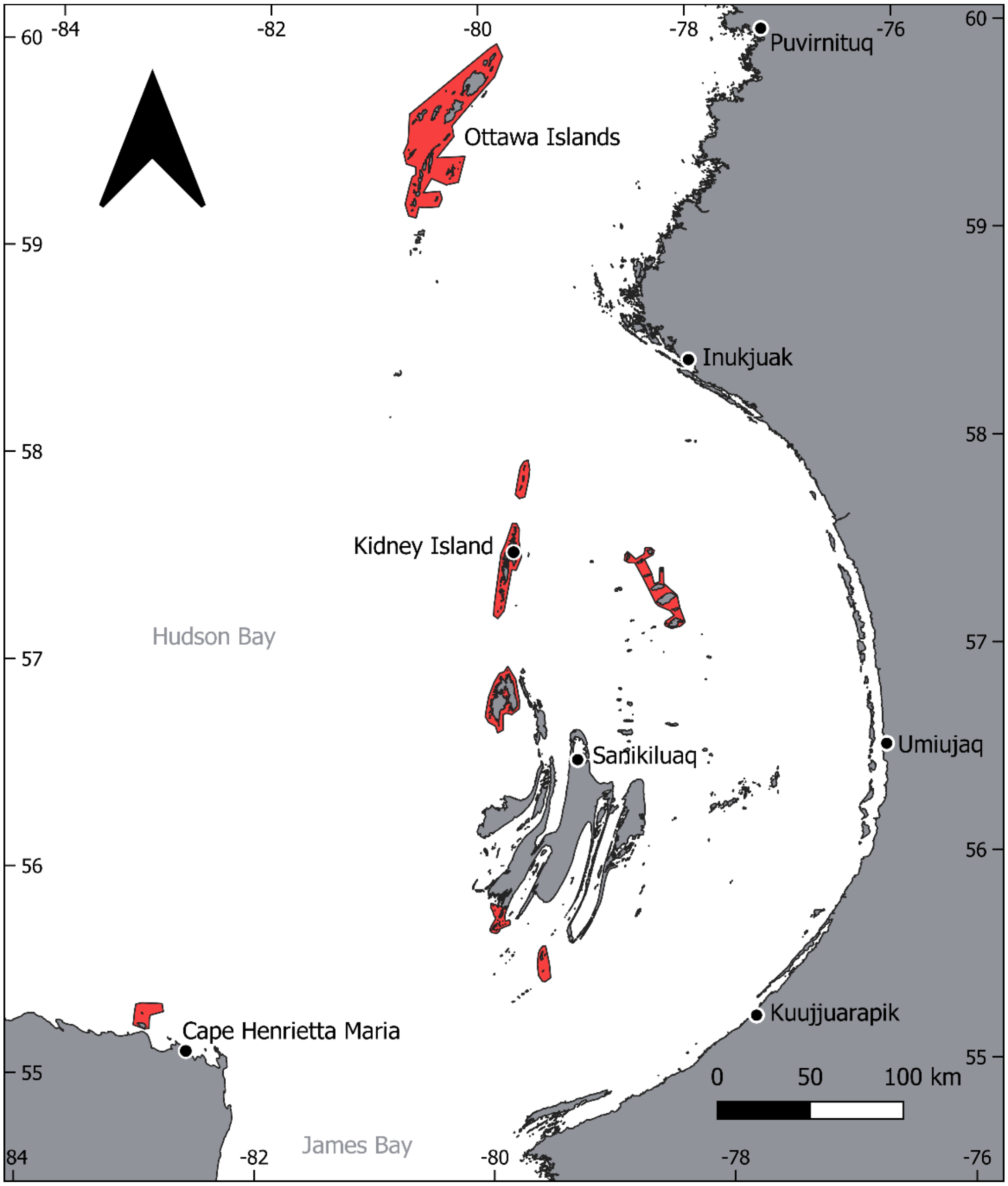

Figure 3. Geographical extent (pink polygons) of satellite imagery collected in southeastern Hudson Bay through tasking of WorldView-3, WorldView-2 and GeoEye satellite constellations via Maxar Technologies between August 11 and October 15, 2022. Latitude and longitude in degrees are indicated along the x- and y-axes.

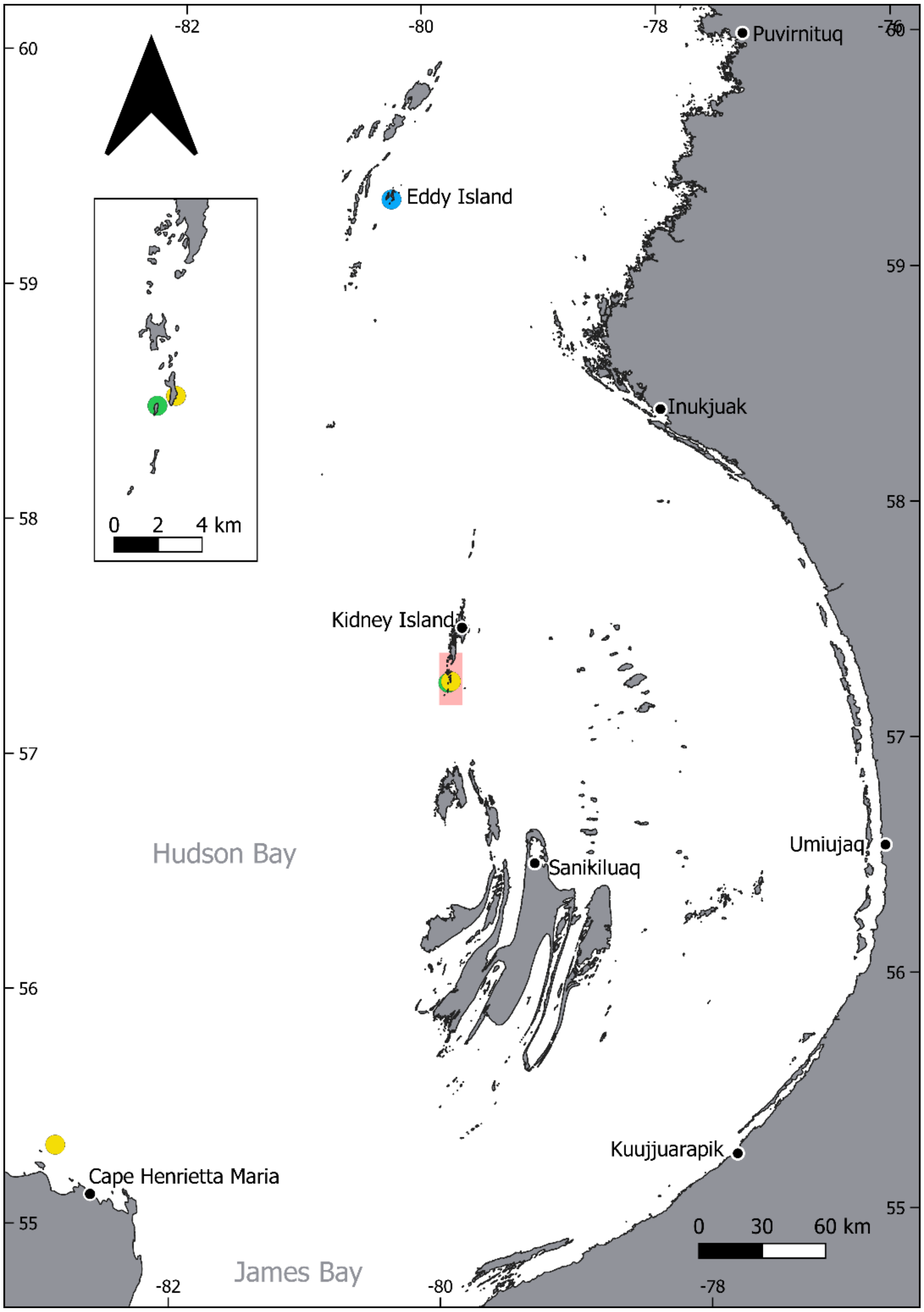

Figure 4. Haul-out sites where walruses were detected during the September 2022 fixed-wing aerial survey (blue circle), on satellite images collected between August and October 2022 (yellow circles), and both during the fixed-wing aerial survey and on satellite images (green circle). The pink polygon illustrates the geographical extent of the inset map displaying the locations of distinct haul-out sites where walruses were detected on Kidney Island. Latitude and longitude in degrees are indicated along the x- and y-axes.

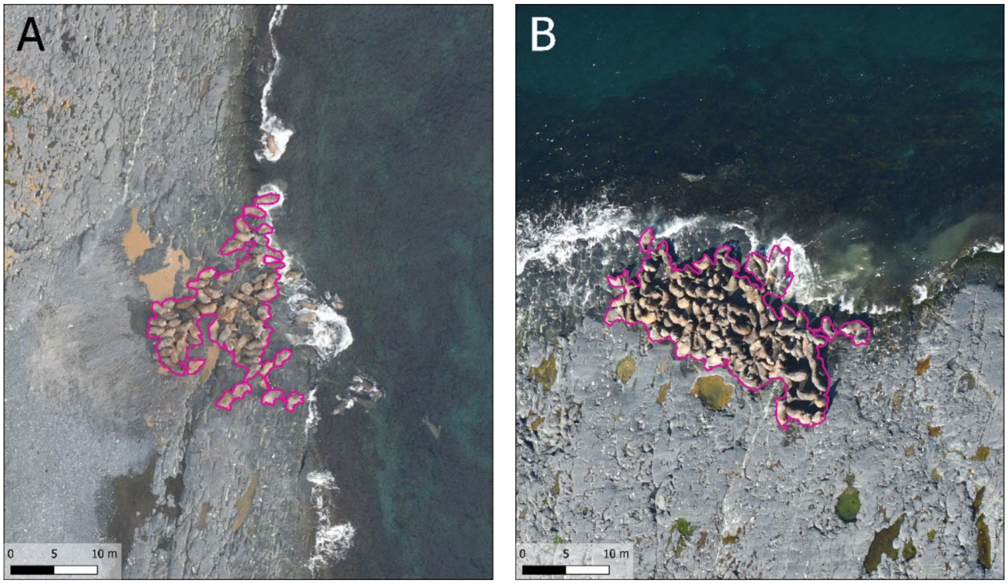

Figure 5. Aerial photographs taken over Kidney Island on September 5 (A) and 10 (B), 2022 during the fixed-wing aerial survey, and displaying walrus aggregations. Pink contours illustrate the polygons drawn around the walrus aggregations, which were used to compute walrus density on the haul-out site. The average walrus density from these two pictures was used to derive walrus abundance from satellite images.

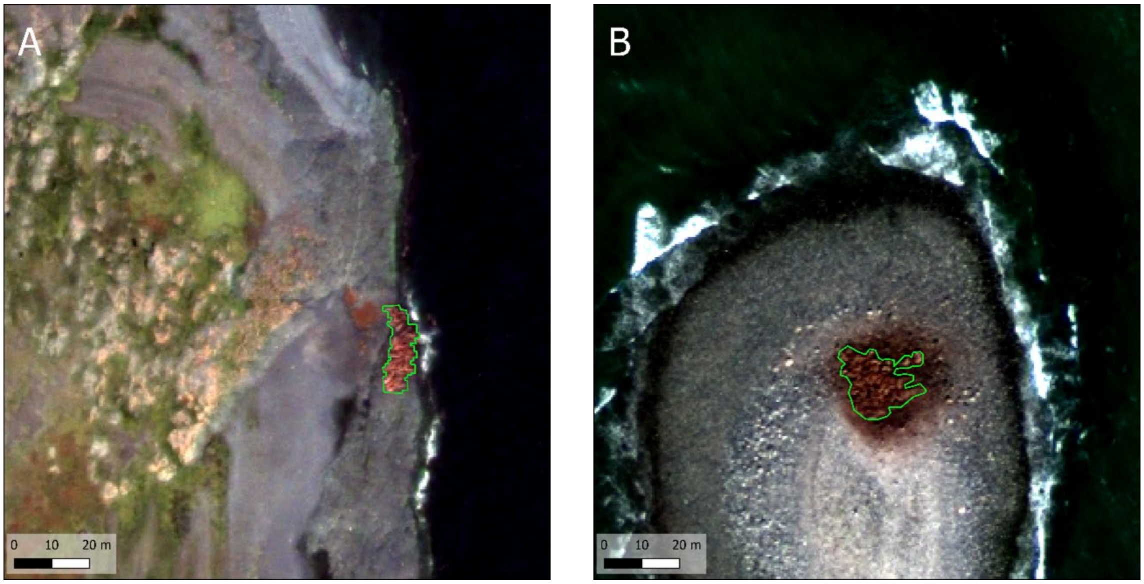

Figure 6. Pansharpened, 30 cm resolution satellite photographs taken over Kidney Island on September 6 and near Cape Henrietta Maria on September 18, 2022 displaying walrus aggregations. Green contours illustrate the polygons drawn around the walrus aggregations. The areas from these polygons were multiplied by walrus densities on haul-out sites derived from aerial photographs to derive walrus abundance from these satellite images.

TABLES

Table 1. Site, position, survey dates, photographic and visual counts of hauled out walrus detected during the aerial survey conducted in September 2022 in the South and East Hudson Bay walrus stock area of distribution. The dates at which satellite imagery has been collected at these haul-out sites, and the number of walrus aggregations detected on satellite photographs are also displayed.

Waypoint Number	Latitude	Longitude	Aerial survey			Satellite images		Comments
			Date covered (mm-dd)	Walrus visual count	Walrus photo count	Date photographed (mm-dd)	Walrus aggregation detected	
1	54° 46.026'	-79° 31.702'	09-07	0	0	*Not covered*	-	-
2	54° 55.266'	-79° 25.478'	*Not covered*	-	-	-	-	Offshore point, no haul-out site
3	55° 34.578'	-79° 32.730'	09-05	0	0	09-06	0	-
						09-12	0	-
4	55° 45.024'	-79° 53.916'	09-05	0	0	09-03	0	-
						09-06	0	-
			09-12	0	0	09-09	0	-
5	56° 02.474'	-80° 00.153'	09-05	0	0	-	-	-
			09-12	0	0	-	-	-
6	56° 03.276'	-79° 56.231'	09-12	0	0	-	-	-
7	56° 39.775'	-80° 00.997'	*Not covered*	-	-	-	-	Offshore point, no haul-out site
8	56° 42.865'	-79° 56.142'	09-05	0	0	08-15	0	-
						08-16	0	-
						08-24	0	-
						09-07	0	-
9	56° 43.621'	-79° 53.315'	09-05	0	0	08-15	0	-
						08-16	0	-
						08-24	0	-
						09-07	0	-
10	56° 46.044'	-79° 57.146'	09-05	0	0	08-15	0	-
						08-16	0	-
						08-24	0	-
						09-07	0	-
						09-09	0	-
11	56° 49.819'	-79° 34.167'	09-05	0	0	08-22	0	-
12	55° 06.320'	-78° 21.612'	09-07	0	0	-	-	-
13	55° 39.962'	-77° 17.358'	09-04	0	0	-	-	Camera system failure
			09-05	0	0	-	-	-
14	57° 47.172'	-77° 03.654'	09-04	0	0	-	-	-
15	57° 22.502'	-78° 27.963'	09-04	0	0	10-12	0	-
						10-15	0	-
16	57° 24.054'	-79° 47.961'	09-05	0	0	08-16	0	-
			09-10	0	0	09-06	0	-
			09-13	0	0	-	-	-
17	57° 40.334'	-79° 42.906'	09-10	0	0	08-16	0	-
						09-06	0	-
18	58° 51.445'	-78° 54.791'	09-13	0	0	-	-	Flown at 300-800’ (low ceilings)
19	57° 53.685'	-79° 38.613'	09-10	0	0	08-11	0	-
						08-24	0	-
						09-09	0	-
20	59° 22.943'	-80° 17.240'	09-04	**1**	**1**	-	-	-
			09-13	0	0	-	-	-
21	59° 31.000'	-80° 24.838'	09-04	0	0	09-09	0	-
			09-13	0	0	10-12	0	Flown at 600’ (low ceilings)
22	59° 38.398'	-80° 17.131'	09-04	0	0	09-09	0	-
						10-12	0	-
23	59° 40.355'	-80° 32.078'	09-04	0	0	10-12	0	-
24	60° 42.823'	-78° 39.352'	09-04	0	0		-	-
25	55° 08.429'	-82° 19.249'	09-10	0	0	09-18	**1**	-
26	57° 19.029’	-79° 51.978’	09-05 *pass 1*	**80**	**114**	08-16	**2**	-
			09-05 *pass 2*	**-**	**126**			Highest count from 2 passes
			09-10 *pass 1*	**52**	**131**	09-06	**1**	Highest count from 2 passes
			09-10 *pass 2*	**-**	**117**			-

Table 2. Site, position, date of collection, area covered by the walrus aggregation and estimated number of walruses hauled out from satellite photographs collected between August 11 and October 15 in the South and East Hudson Bay walrus stock area of distribution.

Haul-out site	Latitude	Longitude	Date of photography	Average area of walrus aggregation (m^2)	Walrus density used as multiplier (CV) (ind·m^{-2})	Estimated number of walruses (CV)
Kidney Island 1	57° 18.600	-79° 51.960’	08-16	99.63	0.44 (0.03)	**44.29 (0.03)**
			09-06	147.78	0.44 (0.03)	**65.69 (0.03)**
Kidney Island 2	57° 19.380’	-79° 50.700	08-16	25.16	0.44 (0.03)	**11.18 (0.03)**
Cape Henrietta Maria	55° 20.640’	-82° 51.720’	09-18	290.60	0.44 (0.03)	**129.17 (0.03)**

Table 3. Potential biological removal (PBR) for the south and east Hudson Bay (SEHB) walrus stock, calculated using different abundance estimates ($\widehat{N_C}$), and a recovery factor of 0.25, and an R_{max} of 0.08.

Abundance estimate used to compute N_{min}	$\widehat{N_C}$ (CV)	PBR
2022 aerial survey	432 (0.55)	**3**
2022 satellite imagery	633 (0.56)	**4**
Combined	496 (0.40)	**4**

Table 4. Reported harvest statistics for the South and East Hudson Bay walrus stock for 1973-2022. (Hammill et al. 2016; DFO Statistics). These numbers do not include animals that were struck and lost.

Year/ Community	Inukjuak	Kuujjuarapik	Umiujaq	Sanikiluaq	**Total**
1973				8	**8**
1974	4	0			**4**
1975	7	1		8	**16**
1976	1	2		7	**10**
1977	4	0		6	**10**
1978	3	0		0	**3**
1979	40	0			**40**
1980	10	0			**10**
1981	7	1		2	**10**
1982	2	0		10	**12**
1983	0	1		3	**4**
1984	15	0		7	**22**
1985	9	1		1	**11**
1986	11	0		2	**13**
1987	12	0		10	**22**
1988	7	0	1	5	**12**
1989	0	0	1	5	**6**
1990	8	1		5	**14**
1991	8	0	0	5	**13**
1992	5	0	0		**5**
1993	9	0	1		**10**
1994	5	0	0		**5**
1995	10	0	0		**10**
1996	11	0	0	2	**13**
1997	5	2	0	4	**11**
1998	8	0	0	20	**28**
1999	0	0	0	1	**1**
2000	0	0	1	0	**1**
2001	0	0	0	0	**0**
2002	0	0	0	15	**15**
2003	4	0	0	3	**7**
2004	0	0	0		**0**
2005	3	0	0		**3**
2006	0	0	0	2	**2**
2007	0	0	0		**0**
2008	8	0	0	0	**8**
2009	0	0	0	2	**2**
2010	0	0	0	2	**2**
2011	0	0	0	2	**2**
2012	0	0	0	3	**3**
2013	5	0	0	0	**5**
2014	0	0	0	0	**0**
2015	7	0	0	1	**8**
2016	4	0	0	0	**4**
2017	0	0	0	1	**1**
2018	0	0	0	3	**3**
2019	0	0	0	0	**0**
2020	0	0	0	0	**0**
2021	0	0	0	5	**5**
2022	0	0	0	0	**0**