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Distribution, abundance, and density of harbor porpoises in Hood Canal, Washington

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Abstract

Harbor porpoises (*Phocoena phocoena*) are the only cetaceans routinely sighted in Hood Canal, a narrow fjord that comprises the western edge of Puget Sound, Washington, USA. Harbor porpoises are sensitive to anthropogenic sounds, including noise from recreational and commercial vessel traffic, and the United States Navy, which conducts military training and testing within Hood Canal that can include underwater sound sources. This study was funded as part of the Navy monitoring program to assess potential impacts of naval activities on cetaceans. We conducted vessel-based line-transect surveys for harbor porpoises in Hood Canal in 2022–2023 to derive seasonal estimates of abundance and density. We carried out surveys over 37 days and surveyed the entire canal twice per season totaling 2,176 km of on-effort track line. We recorded 809 on-effort harbor porpoise groups and 1,385 individuals. Seasonal abundance estimates were lowest in winter (308 animals, 95% CI = 189–503) and gradually increased through spring and summer to a peak of 1,336 animals (95% CI = 826–2,160) in fall. Overall porpoise density was highest in central Hood Canal, an area that includes a designated United States Navy training range, though porpoise sightings were notably absent in a 21-km^2 area adjacent to the naval submarine base within this otherwise high-density region. Though we collected only a single year of data, these results suggest that harbor porpoise abundance in Hood Canal increased significantly since it was last estimated (2013–2015). The notable seasonal fluctuation of harbor porpoise abundance suggests Hood Canal may host a larger percentage of the overall Washington Inland Waters stock during the fall season, raising important management considerations.

KEYWORDS

abundance estimation, anthropogenic sound, distance sampling, harbor porpoise, *Phocoena phocoena*, Salish Sea

The harbor porpoise (*Phocoena phocoena*) is a broadly dispersed, cold-water species that inhabits coastal and continental shelf waters of the Northern Hemisphere (Bjørge and Tolley 2002, Hammond et al. 2013). With a global population estimate of >1,000,000, they are classified as least concern on the International Union for Conservation of Nature Red List (Braulik et al. 2020); exceptions are the Baltic Sea subpopulation (Hammond et al. 2016) and the Black Sea subspecies (Birkun and Frantzis 2008). Their exclusively coastal distribution increasingly brings them into contact with humans in the developed parts of their range and they likely have much finer-scale population structure than many existing management units reflect (Calambokidis and Barlow 1991, Hanson et al. 1999, Rosel et al. 1999, Chivers et al. 2002, Hanson 2007); therefore, local-scale research is warranted where porpoises are exposed to high levels of anthropogenic activity.

In the eastern North Pacific, there are 6 federally managed stocks of harbor porpoises in United States waters between the borders with Mexico and Canada, including 2 designated stocks in Washington: the Northern Oregon-Washington Coast and Washington Inland Waters stocks (Carretta et al. 2022). The Inland Waters stock boundary encompasses the United States waters of the Juan de Fuca Strait, San Juan Islands, and Puget Sound (Carretta et al. 2022), which is part of the Salish Sea, a marginal sea of the Pacific Ocean. The Washington Inland Waters stock has no special management status under the Marine Mammal Protection Act or the Endangered Species Act in the United States; however, the harbor porpoise is federally managed as a species of special concern under Canada's Species at Risk Act, given its exposure to high and rising levels of human activity, especially in interior United States and Canada boundary waters (Department of Fisheries and Oceans Canada 2009). Elliser and Hall (2021) provide a detailed treatise on the past, present, and future of the harbor porpoise in the Salish Sea, including the decline and range contraction of the Washington Inland stock from the 1940s–1970s followed by its subsequent resurgence, with partial reoccupation of the historical stock range, beginning in the early 2000s.

The impetus for this project was to collect fine-scale marine mammal occurrence data in Hood Canal, a narrow fjord constituting the west side of Puget Sound, with emphasis on harbor porpoises, to improve impact assessments related to United States Navy activities that occur in the area. The Northwest Training and Testing study area (Figure 1) in Washington comprises multiple Navy ranges in the offshore, nearshore, and inland waters. The Northwest Training and Testing study area provides an environment that ensures naval forces have the capabilities and readiness to complete assigned missions, and supports a variety of aerial, surface, and subsurface exercises, many of which introduce sound to the water (Department of the Navy 2020). The Dabob Bay Range Complex (DBRC) is a training and testing area inside Hood Canal. It is part of the Naval Sea Systems Command's Naval Undersea Warfare Center Keyport Range (Complex). Hood Canal is also home to Bangor Submarine Base, which is part of Naval Base Kitsap (Figure 1).

Cetaceans are susceptible to anthropogenic disturbance. Potential sources of disturbance include vessels, fishing activities, marine construction, and the use of underwater active acoustic devices, all of which can occur in

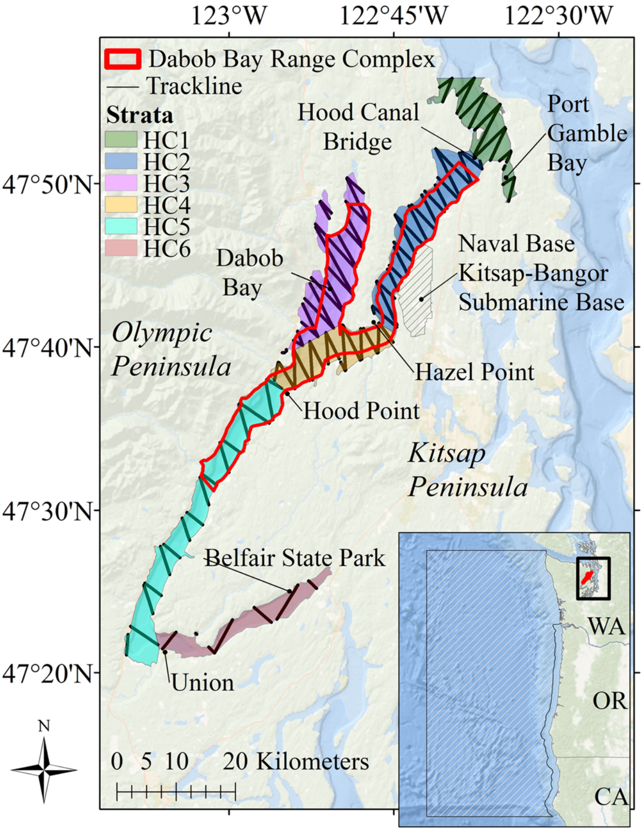

FIGURE 1 The 2022–2023 Hood Canal harbor porpoise study area in Washington, USA. This figure includes the inshore and offshore Northwest Training and Testing boundaries, the Dabob Bay Range Complex located within Hood Canal, the 6 survey strata, and an example of the randomized transect design within each stratum.

Hood Canal. Although porpoises may be influenced by all these activities to some degree, anthropogenic sounds within the species' hearing range appear to be most disturbing (Noren et al. 2017). These include but are not limited to sonar (Parsons 2017), pingers (Dawson et al. 2013), high-frequency vessel noise (Hermannsen et al. 2014, Dyndo et al. 2015), and sounds associated with construction and operation of wind turbines (Carstensen et al. 2006, Benhemma-Le Gall et al. 2021). A review by Noren et al. (2017) concluded that the most common reaction of odontocetes disturbed by an acoustic source was to cease echolocation and leave the area, leading to a functional disruption of energy acquisition when these sound sources are introduced in foraging areas. Thus, acoustic disturbance may be costly for species with high foraging rates or limited foraging ranges if sound exposure is prolonged or frequent (Wiśniewska et al. 2016).

Harbor porpoises are protected under the Marine Mammal Protection Act of 1972. To conduct military activities, the United States Navy obtains a marine mammal permit issued by the National Marine Fisheries Service and is required to monitor the effects of its permitted activities on protected species (Department of the Navy 2020). A take, as defined under the Marine Mammal Protection Act, means to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal (16 U.S. Code 1362). When acquiring these permits, the number of takes requested are evaluated relative to population size. Seasonal abundance, distribution, and density of local species are used to assess the overlap of activities and animals, both of which may fluctuate throughout the year. Despite their importance to take estimation, seasonal occurrence data are historically limited for marine mammals in Hood Canal.

Since 2003, limited marine mammal research in Hood Canal has occurred, primarily on harbor seals (*Phoca vitulina*) rather than cetaceans (London et al. 2012, Ampela et al. 2021, Jefferson et al. 2021). The existing harbor porpoise abundance estimate for Hood Canal, 185 harbor porpoises (95% CI = 116–291), was calculated from aerial surveys conducted 2013–2015 (Jefferson et al. 2016). Small sample sizes within the canal precluded further seasonal assessment, but when all areas were pooled together within the greater Puget Sound study area, seasonal fluctuations in numbers were observed between spring, summer, and fall (Jefferson et al. 2016). The expanding recolonization of the Inland Waters stock within Puget Sound proper is well documented (Calambokidis et al. 1997, Huggins et al. 2015, Evenson et al. 2016, Carretta et al. 2022). A 33.8% growth rate was documented between 2000 and 2014 (Evenson et al. 2016). If this trend were to continue, this would suggest that the 7-year gap since a marine mammal abundance study within the canal (Jefferson et al. 2016) would no longer be representative of present-day harbor porpoise numbers.

There are observational challenges with harbor porpoises that contribute to very high uncertainty in abundance estimates, particularly those derived from aerial surveys, including their small physical size, inconspicuous coloration, and cryptic surfacing behavior. It is suggested that vessel-based surveys detect 2–3 times as many sightings/km as aerial surveys (Dahlheim et al. 2015, Jefferson et al. 2016), and thus have the potential to estimate abundance with higher confidence. This is particularly true in narrow bodies of water with high shorelines, such as Hood Canal, where viewing times from comparatively fast-moving aircraft are limited. Aerial surveys may also struggle to detect animals that occur very near shore, which represents a much greater proportion of habitat in narrow waterways.

Our primary objective of this year-long study was to conduct vessel-based line-transect surveys to systematically collect cetacean occurrence data within Hood Canal, use these data to update estimates of harbor porpoise density and abundance, and describe spatial and seasonal variation in their distribution and habitat use. Our second objective was to develop a trackline detection probability correction derived specifically for vessel-based harbor porpoises in this region. Our third objective was to conduct seasonal experiments to assess the effects of observer distance estimation error under varying environmental conditions that may influence harbor porpoise sighting detection.

STUDY AREA

Hood Canal (47.60°N, 122.95°W) is located within the Salish Sea in Washington (Figure 1). This long, narrow fjord in western Puget Sound separates the Olympic and Kitsap Peninsulas. This region is characterized by a maritime climate of mild, wet winters and dry, warm summers influenced by the Pacific Ocean and Olympic Mountain range located west of the canal. Hood Canal is 110 km long with an average width of 2.4 km, and total area of 370 km^2. The average depth is 54 m (max. = 183 m). The topography of the canal is a combination of steep sloping shorelines, a deep main channel and shallow coastline particularly near estuaries, bays, and harbors that are tidally influenced. The annual surface water temperature range is 6.8–21.5°C (National Data Buoy Center, 2016–2022, stations 46122, 46124, 46125). Several rivers and tributaries feed into Hood Canal. It is home to all 8 species of salmon and trout that use marine and freshwater systems in the Pacific Northwest, including the threatened Hood Canal summer-run chum salmon, Chinook salmon (*Oncorhynchus tshawytscha*), steelhead trout (*Oncorhynchus mykiss*), and bull trout (*Salvelinus confluentus*), designated under the Endangered Species Act. Additional marine mammal sightings include harbor seals, California sea lions (*Zalophus californianus*), river otters (*Lutra canadensis*), Steller sea lions (*Eumetopias jubatus*), and Bigg's killer whales (*Orcinus orca*) with the occasional encounters with endangered Southern Resident killer whales, humpback whales (*Megaptera novaeangliae*), Dall's porpoises (*Phocoenoides dalli*), and minke whales (*Balaenoptera acutorostrata*). Along with year-round Naval use, the canal experiences fluctuations in seasonal subsistence, recreational, and commercial fishing activity. This study occurred during all 4 seasons between February 2022–2023. Seasons were winter (22 Dec–20 Mar), spring (21 Mar–20 Jun), summer (21 Jun–21 Sep), and fall (22 Sep–21 Dec).

METHODS

We divided the survey area into 6 strata of varying geometry (Figure 1) to facilitate allocation of survey effort and improve sampling efficiency (Strindberg and Buckland 2004). Stratum 1 spanned an area of 40 km^2 (12.1% of the study area) and encompassed the entrance of Hood Canal, south to the Hood Canal Bridge, including Port Gamble Bay. Stratum 2 corresponded to an area of 73 km^2 (19.3% of the study area) spanning from the Hood Canal Bridge to just south of Naval Base Kitsap Bangor at Hazel Point. Stratum 3 spanned an area of 75 km^2 (19.8% of the study area) and encompassed all of Dabob Bay. Stratum 4 corresponded to an area of 50 km^2 (13.2% of the study area) encompassing the area from Hazel Point across the mouth of Dabob Bay and south to Hood Point. Stratum 5 corresponded to an area of 96 km^2 (25.3% of the study area) from Hood Point to Union. Stratum 6 corresponded to an area of 39 km^2 (10.3% of the study area) from Union to Belfair to the tidal flats at the distal end of the canal.

We designed the surveys using custom-made functions and libraries developed for the open-source software R (version 4.2.1; R Core Team 2021). These functions allowed us to evaluate survey design based on vessel speed, total survey duration each day (a function of daylight hours during the shortest survey), total survey area covered, and different line-type samplers (e.g., parallel transects, zig-zag transects). After an exploratory analysis of the survey needs, we selected an unequal spacing zig-zag design (Strindberg and Buckland 2004; Figure 1) to efficiently sample the study area taking into account the survey platform, survey logistics, and the complex characteristics (e.g., relatively narrow channels) of the habitats within the canal (Strindberg and Buckland 2004, Thomas et al. 2007). We allocated survey transects using the package dssd (Marshall 2021) in software R. We created stratum- and season-specific systematic zig-zag survey designs with a random starting point. We allocated a slightly higher effort per unit of area to strata 1–4 (Figure 1; Table 1) to thoroughly cover the areas with the highest expected concentrations of harbor porpoises based on previous work (Jefferson et al. 2016) and to provide more coverage to areas that the United States Navy uses for training and testing. Strata 2–4 and the northern half of stratum 5 contain 2 focal areas of naval operations, the DBRC and Naval Base Kitsap Bangor (Figure 1). We projected an estimated 10 survey days per season to provide adequate sample sizes for seasonal density estimates, with each stratum surveyed twice (e.g., 2 unique, randomly generated survey designs would be completed each season).

We carried out vessel surveys in passing mode (i.e., the vessel did not divert from the transect to close in on detected cetacean groups; Hiby and Hammond 1989, Hammond et al. 2021), using the R/V On Porpoise, an 8.2-m research vessel with upper and lower decks. Four observers rotated through 3 observation positions during each survey day. Port and starboard primary observers were located on the upper deck, positioned with an average eye-height of 3.40 m above water, and one independent observer was positioned on the main deck with an average eye-height of 2.11 m above the water. Observers on upper and lower decks could not see or hear one another while surveying. Port and starboard observers searched for marine mammals from the beam (90°) of their respective side to approximately 10° on the opposite side of the survey line using the naked eye. The independent observer surveyed from −90° to 90° with the naked eye. The boat operator was responsible for recording environmental conditions and transect effort and maintaining survey speed (~10 knots), and was not involved in active searching.

Each observer used a clock, an angle board, and a voice recorder to document the distance and relative angle to all cetacean sightings. They also documented any pinniped species that surfaced within approximately 100 m from the boat, a distance at which a rapid, accurate, species determination could be made quickly with the naked eye. All clocks were calibrated to global positioning system (GPS) time prior to each survey. For each sighting, the observers recorded time, species, angle (degrees relative to the bow), estimated radial distance (m), and minimum, best, and maximum estimates of group size. We logged effort data using a custom-built Microsoft Access (Microsoft, Redmond, WA, USA) database on a ruggedized tablet with an integrated GPS. Vessel position information was automatically logged every 5 seconds (sec) using the vessel's GPS. The boat operator entered environmental information at the start of each transect and when conditions changed: visibility, precipitation and atmospheric conditions, cloud cover, sea state (Beaufort scale), swell height, glare angle (degrees relative to bow), glare severity (proportion of the field of view obscured by glare), and overall observational quality, a subjective score which takes into consideration the combined

TABLE 1 Strata, number of transects, trackline surveyed (km), transects completed (*n*), and on-effort harbor porpoise sightings of groups and individuals (ind) in the groups by season used to calculate seasonal density and abundance in Hood Canal, Washington, USA, 2022–2023.

		Spring			Summer			Fall			Winter			All seasons		
Stratum	Total transects	Effort (km)	*n*	Groups (ind)	Effort (km)	*n*	Groups (ind)	Effort (km)	*n*	Groups (ind)	Effort (km)	*n*	Groups (ind)	Effort (km)	*n*	Groups (ind)
1	29	82.03	29	15 (27)	71.14	25	33 (55)	77.52	26	5 (8)	74.70	26	14 (26)	304.39	106	67 (116)
2	42	129.72	41	89 (143)	129.58	40	142 (192)	131.16	41	51 (101)	122.09	42	19 (31)	512.79	164	301 (467)
3	35	135.33	34	6 (14)	128.04	33	37 (59)	136.16	34	93 (186)	127.22	33	3 (7)	526.75	134	139 (266)
4	30	98.14	29	94 (157)	89.98	28	80 (138)	92.10	30	29 (51)	99.11	29	45 (106)	379.33	116	248 (452)
5	32	88.08	31	1 (2)	86.27	31	11 (12)	92.27	32	32 (55)	87.17	32	5 (8)	353.79	126	49 (77)
6	12	25.44	12	0	24.06	12	1 (1)	25.12	11	4 (6)	24.12	10	0	98.74	45	5 (7)
Total	180	557.74	176	205 (343)	529.07	169	304 (457)	554.57	174	214 (407)	534.41	172	86 (178)	2,175.79	691	809 (1,385)

effects from all these factors. The operator logged the time and position at the start and end of each transect and anytime effort was paused or resumed during a transect because of navigational hazards or weather. Weather and visibility conditions changed frequently with the potential to influence the observer search pattern. Observations occurred during adequate light, began no earlier than 30 minutes after sunrise, ended no later than 30 minutes before sunset, and were suspended in poor visibility conditions or a sustained sea state at or above Beaufort 3. Observers maintained search effort under light precipitation and under foggy conditions when the visibility was >1 km but ceased effort in sustained moderate to severe precipitation or if visibility was <1 km.

Because observers estimated the radial distance to sightings with the naked eye, we conducted experiments to assess distance estimation error for each observer under varying conditions, which we then used to correct field estimates *post hoc*. We repeated the experiment at least once each season for all observers. During these experiments, observers independently estimated distance to a moored object that resembled the dorsal fin and back of a harbor porpoise. The boat was repositioned at various distances and angles from the fixed porpoise model with the goal of collecting observer distance estimates across a range of circumstances encountered during a typical transect (e.g., close shoreline, land reflection, glare). We obtained up to 20 estimations from each observer during each experiment, with trials split evenly between the lower and upper decks. The boat operator recorded the true distance to the object, as determined by the vessel GPS, and revealed the distance to the observers after recording an estimate in the first half of the trials from each level, but the operator did not reveal distances for the second half of trials. In addition to the estimated distance, each observer recorded the visual conditions at the target as potential predictors of distance. We used a regression framework to derive a distance correction function for each observer (Williams et al. 2007). We conducted exploratory analyses to assess the relationship of the response variable (true distance) and the various predictors and to evaluate covariance among predictors (Figures S1 and S2, available in Supporting Information).

We used generalized linear models to model true distance as a function of 6 numeric (true distance, estimated distance, sea state, cloud cover, visibility conditions, glare) and 2 factor (observer, background conditions) predictor variables (Table S1, available in Supporting Information). Models included all combinations of these variables in an additive fashion. We log-transformed true and estimated distances before analysis to maximize normality of model residuals, which we confirmed after model fitting using a Shapiro-Wilk normality test. We used Akaike's Information Criterion (AIC) for model selection and used the model with the lowest score (the most supported model) for computing the predicted true radial distances from those estimated for sightings detected by the observers during the actual surveys. We conducted all analyses in the software R (R Core Team 2021).

Line-transect analytical methods are relatively well developed for estimating density and abundance of marine mammals using visual sighting data (Buckland et al. 2001, 2004). One of the main assumptions of this method is that all objects (a group of marine mammals in this study) are detected with certainty on the survey line, i.e., the trackline detection probability g(0) = 1. Because of their elusive behavior, marine mammals, especially harbor porpoises, are often missed by observers and the g(0) = 1 assumption is rarely met (Laake et al. 1997). Therefore, we computed estimates of the proportion of groups of animals missed on the transect (perception bias) by treating sighting data from the upper and lower observation positions as independent platforms.

To identify duplicate sightings between the upper and lower observers, we compared the time, angle, radial distance, linear distance (as calculated from the corrected radial distances), and group size estimates among all harbor porpoise sightings on the same day (Palka 2000, Sucunza et al. 2022). We considered all upper-lower sighting pairs that were recorded within 90 seconds and within 300 m linear distance of each other as potential matches; there could be multiple potential matches for a single sighting in areas of high sighting density. This resulted in 391 sighting pairs that were then manually evaluated by a single analyst to identify which were likely to be the same group of animals and which were not. While the offset data were seldom identical across observers because of factors such as the use of visual estimates, the potential for human error, and animal behavior, we considered a sighting by the lower observer a match to a sighting by an upper observer when the differences among all offsets were plausible (e.g., where the first observer to record the sighting had a shallower angle than the second, the sighting was on the same side of the transect, and the difference in the radial distance estimates were within expected levels for estimation error and the time lag between the 2 records).

To record matches, the lower sighting was associated with the sighting number from the corresponding upper sighting, and we used the sighting number to exclude the lower sighting from the reconciled data set for analysis and to flag the upper sighting as having been recorded by the lower. The exception was a small number of cases where multiple upper sightings were recorded as a single, larger sighting by the lower observer. In these cases, the additional matching sightings from the upper observers were associated with the corresponding lower sighting number to flag them as sighted by the lower. We then conducted a secondary review of the mapped sightings to identify any additional matches that may have been missed in the initial screening using offset data.

We performed data analysis using mark-recapture distance sampling methods (Laake and Borchers 2004), which is an extension of standard line-transect analysis. In mark-recapture distance sampling, the probability of sighting a cetacean group is the product of 2 components. The distance sampling component specifies the probability of an observer detecting a cetacean group as a function of its distance from the survey line (with the probability of detection declining as distance from the transect increases) or of other covariates (e.g., group size, visibility conditions). The mark-recapture component corresponds to a conditional detection function and is defined as the probability of one team of observers (e.g., primary) detecting the animal group, given the other team (secondary) has detected it and given the group's distance from the survey line. Mark-recapture distance sampling methods allow for estimation of the proportion of the detection probability on the transect, g(0), and also allow for the use of environmental or biological covariates in the estimation of detection probabilities.

We conducted data analysis using custom-made functions and libraries (e.g., package mrds; Laake et al. 2020) in software R (R Core Team 2021). We estimated detection probability using the point independence approach (Laake 1999, Laake and Borchers 2004, Borchers et al. 2006). We used sighting data from the upper and lower platforms in the mark-recapture models for estimation of the probability of detection on the transect. Because observers in these 2 positions were independent (they were visually and acoustically isolated), we developed capture histories based on sightings made only by the upper or the lower platform, or by both platforms (Laake and Borchers 2004). All models proposed for the mark-recapture component of the model included distance from the transect as a covariate. Other environmental or biological covariates considered included conditions of glare, harbor porpoise group size, sea state, season, and visibility conditions. These covariates were included in the models in an additive fashion to model heterogeneity in detection probability. Once the most supported mark-recapture model was selected, we estimated the distance sampling model (the detection function) by fitting a half-normal or a hazard rate model with and without covariates (cloud cover, glare, group size, sea state, and visibility conditions) similar to our mark-recapture modeling methods. We fit detection functions to unbinned perpendicular distance data truncated at 200 m. We performed model selection for both the mark-recapture and the distance sampling components using AIC and based inference on the most supported model.

We computed estimates of density and abundance of harbor porpoises by pooling data across each of the 2 completed survey designs within each season. We estimated stratum-specific estimates of density and abundance, corrected for perception bias, using the Horvitz-Thompson estimator (Borchers and Burnham 2004). We obtained expected mean group size as specified by Innes et al. (2002) and Marques and Buckland (2003). We estimated variance of the quantities of interest and 95% confidence intervals as described by Buckland et al. (2001) and Innes et al. (2002) as implemented in package mrds.

We computed seasonal density for each survey stratum in each season. We estimated overall density in the whole study area as the average density across all strata, weighted by their areas. We computed abundance in each stratum by multiplying the estimated density by the area of each stratum. We calculated the overall abundance in the Hood Canal study area as the sum of the stratum-specific abundances.

RESULTS

We completed 691 transects totaling 2,175.8 km of trackline in 37 days between 9 February 2022 and 8 February 2023 (Table 1; Figure 2). We surveyed the canal twice in each of the 4 seasons. We recorded 809 on-effort harbor porpoise sightings, totaling 1,385 individuals across all 4 seasons (Table 1; Figure 2). We recorded another 118 off-effort sightings, totaling 223 individuals on transits to and from the survey area, between transects, or when effort was temporarily suspended throughout the day. We plotted off-effort sighting locations to provide a more complete view of seasonal distribution but did not use them in density and abundance estimation (Figure 2).

The most supported model of the calibration experiments suggested that estimated distance and target contrast were the only significant predictors of true distance, indicating that observers were unable to accurately estimate true distance and that distance estimation was influenced by target contrast. Target contrast is the result of complex interactions among a variety of environmental conditions (e.g., solar angle and altitude, cloud cover, land reflection, water surface) and was not recorded as a simple variable for each sighting during surveys; thus, we did not use this model to compute the predicted true distance for sightings. Instead, we used the next best model, which only included estimated distance as a covariate. The model contained a statistically significant intercept term ($\beta = 1.016$, $SE = 0.065$, $t = 15.628$, $P < 0.001$) and showed that the log of estimated distances underestimated true distances ($\beta = 0.807$, $SE = 0.013$, $t = 60.264$, $P < 0.001$). This demonstrates that observers tend to underestimate distance when detecting objects with their naked eye. Without calibration, underestimation would result in positive biases in the estimates of density and abundance. Distance estimation error did not differ by observer.

Spatial and seasonal variation in harbor porpoise sightings was readily evident (Table 1; Figure 2). Most sightings occurred in strata 1–4, with the highest numbers in lower stratum 2 and all of stratum 4 in spring and summer. An increase in sightings in stratum 3 (Dabob Bay) in the fall corresponded with a decrease in lower stratum 2 and stratum 4. Sightings in stratum 1 were highest during summer and lowest in fall. Sightings in the southern half of Hood Canal, strata 5 and 6, were least frequent, but highest in fall.

The number of sightings used to estimate detection probability after truncating the perpendicular distance data at 200 m was 624. Of these, 484 sightings were seen by the primary platform, 290 were seen by the secondary platform, and 150 sightings were seen by both platforms (duplicate sightings).

The most supported detection probability model according to AIC included distance, group size, and season in the mark-recapture component and the hazard rate function without covariates for the distance sampling model (Tables S2, S3, available in Supporting Information). This model suggested that detection probability decreases with distance from the trackline and increases with group size (Table 2; Figure S3, available in Supporting Information). It also indicated that detection probability varied by season. The expected harbor porpoise group size ranged seasonally from 1.43 (summer) to 1.77 individuals (winter; Table 3), but these seasonal differences were not statistically significant.

Density and abundance estimates indicated a seasonal pattern in the overall occurrence of harbor porpoises in Hood Canal (Table 3; Figure 3A). Seasonal abundance estimates for the entire canal ranged from 308 animals in winter to 1,336 in fall (Table 3; Figure 3A). Though the estimates between fall and summer and between spring and winter are not statistically different, they suggest that harbor porpoises are most abundant in Hood Canal in the summer and fall and that they leave Hood Canal in winter, and gradually return in spring. Stratum-specific estimates (Figure 3B) suggested that year-round harbor porpoise abundance is highest in strata 2 and 4. This area corresponds to the middle of Hood Canal, which falls within the DBRC and includes the Bangor Submarine Base (Figure 4). One notable exception in this area was the absence of harbor porpoise sightings (except for 1 fall survey day) in a 21-km^2 area in the section of the DBRC where the in-water physical structures are associated with the base. Abundance by season was highest in stratum 3 in fall (Figure 3B). In general, abundance was substantially lower in both the northern (stratum 1) and southern ends (strata 5 and 6). Fall abundance estimates for strata 5 and 6 were higher than other seasons, but the confidence intervals for all seasons were wide in these strata, suggesting that, at least for stratum 6, the fall estimate did not differ from the other seasons.

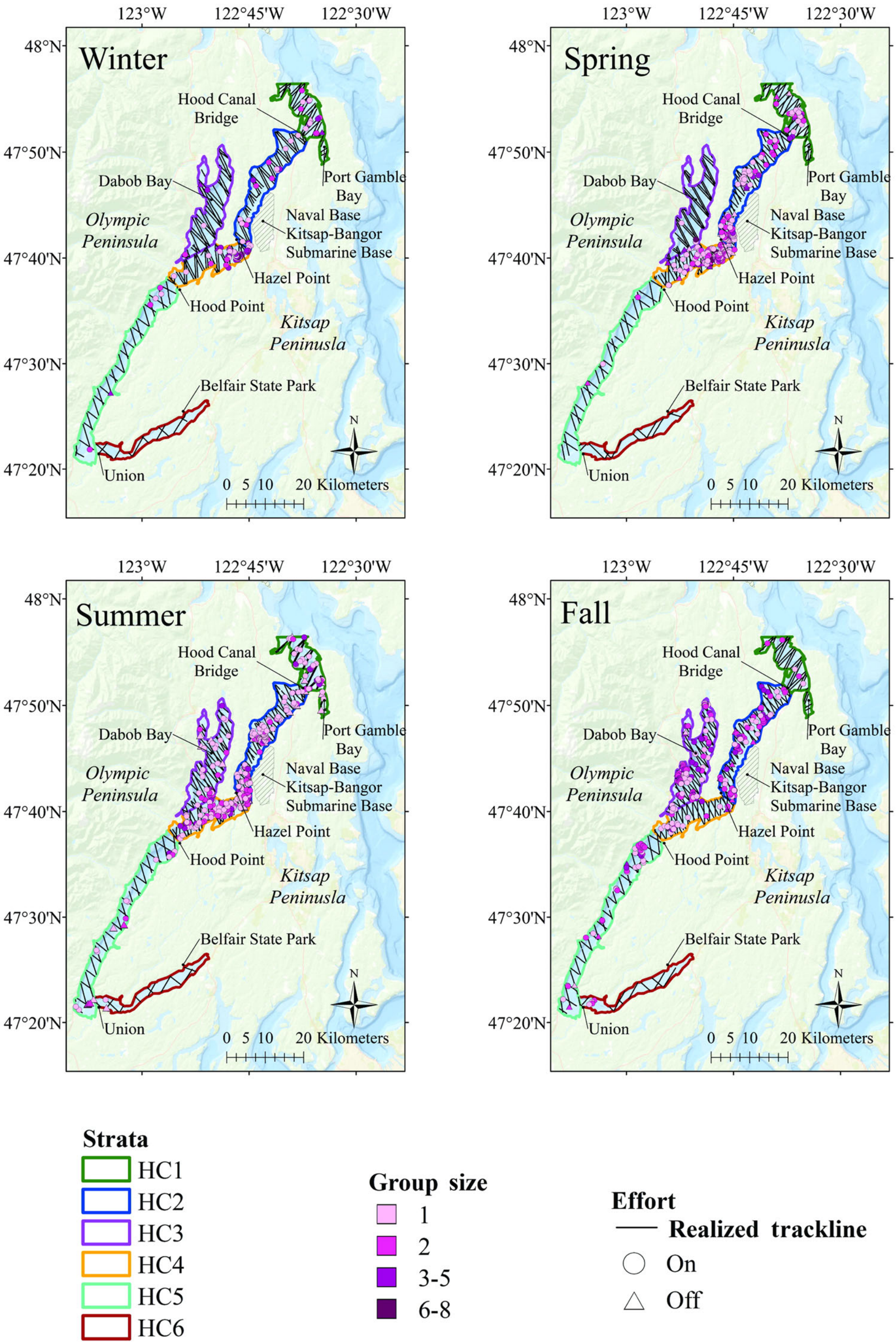

FIGURE 2 Seasonal survey effort and harbor porpoise sightings in Hood Canal, Washington, USA, 2022–2023. We indicate the 6 strata of the study area, the group size of sighted porpoises, and whether we sighted the porpoise during the trackline survey (circles) or opportunistically during travel to and from the survey (triangles). Seasons are defined as winter (22 Dec–20 Mar), spring (21 Mar–20 Jun), summer (21 Jun–21 Sep), and fall (22 Sep–21 Dec).

TABLE 2 Parameter estimates from the most supported detection probability (p) model for harbor porpoise sightings in Hood Canal, Washington, USA, 2022–2023.

Parameter	Estimate	SE	CV
Mark-recapture model			
Intercept	−0.626	0.301	
Distance	−4.522	1.892	
Group size	0.398	0.099	
Season (summer)	0.315	0.236	
Season (fall)	−1.281	0.326	
Season (winter)	−0.232	0.352	
Average $p(0)$	0.618	0.063	0.10
Distance sampling model			
Scale coefficient	−1.932	0.076	
Shape coefficient	0.783	0.281	
Average $p(0)$	0.802	0.034	0.04
Average p	0.496	0.054	0.11

TABLE 3 Quantities of interest for seasonal estimation of abundance of harbor porpoises in Hood Canal, Washington, USA, 2022–2023. (n = number of groups seen by the upper observation platform, ER = encounter rate, ES = expected group size, D = density of individuals per km^2, N = number of individuals).

	Season			
Metric	Spring	Summer	Fall	Winter
Number of groups[a]	152	245	161	66
Encounter rate	0.07	0.113	0.074	0.03
CV	0.21	0.15	0.16	0.24
Group size	1.59	1.43	1.62	1.77
CV	0.05	0.03	0.04	0.06
Density (porpoises/km^2)	2.444	2.152	3.524	0.812
CV	0.19	0.14	0.25	0.25
Number of porpoises	547	815	1,336	308
Lower 95% CL	375	623	826	189
Upper 95% CL	796	1,066	2,160	503

[a] Number of groups observed on the upper observation platform.

DISCUSSION

The results of this study represent a comprehensive assessment of harbor porpoises in Hood Canal. They provide seasonal- and stratum-specific density and abundance estimates using a g(0) correction derived specifically for vessel-based harbor porpoises in this region. These findings suggest that a relatively large number of harbor porpoises inhabit Hood Canal, especially in the summer-fall period, but most porpoises leave the canal in winter.

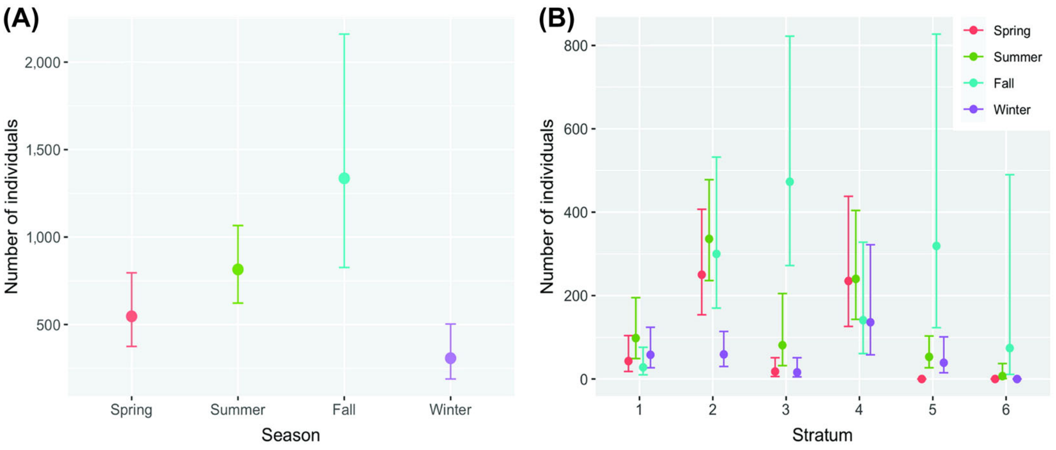

FIGURE 3 Seasonal estimates (A) of abundance for harbor porpoises (and 95% CI) for all of Hood Canal, Washington, USA, and by stratum (B), 2022–2023.

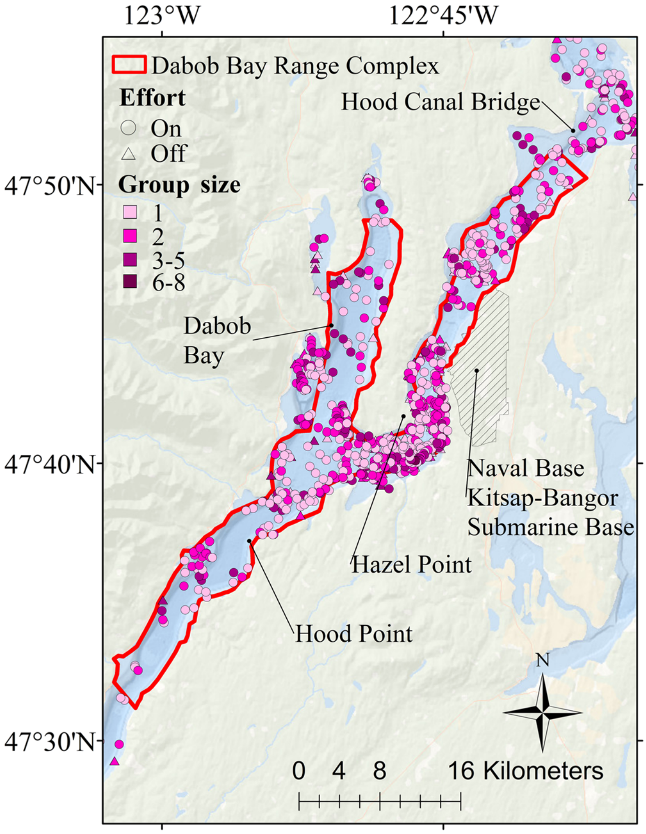

FIGURE 4 Harbor porpoise sightings within the Dabob Bay Range Complex located in Hood Canal, Washington, USA, 2022–2023. We indicate the group size of sighted porpoises, and whether we sighted the porpoise during the trackline survey (circles) or opportunistically during travel to and from the survey (triangles).

The overall group size for this species was estimated at 1.6 individuals/group, which is consistent with previous estimates of group sizes of this species in Hood Canal (Jefferson et al. 2016) and in other regions (Dahlheim et al. 2015, Zerbini et al. 2022).

The fall abundance estimate was considerably higher than the other seasons. This estimate was heavily influenced by a low number of duplicate sightings across the upper and the lower platforms, particularly on several days with very high numbers of sightings. The proportion of groups seen by both platforms was greater in winter (0.17), spring (0.20), and summer (0.23) compared to fall (0.09). Detection probability is computed as a function of these matches, so a low matching rate indicates that a high proportion of animals is missed by the upper observer; that is, g(0) is much lower. Because abundance is inversely proportional to detection probability, a low detection probability will result in a high estimate in the number of individuals.

While it was clear there were many more porpoises present in fall, we did not expect the duplicate sightings across platforms to vary seasonally, given the same observers surveyed in all seasons and rotated across all observation positions. One potential source of heterogeneity in the data was a seasonal change in behavior that reduced surface availability of porpoises relative to other seasons. Teilmann et al. (2012) reported tagged harbor porpoises in the North and Baltic seas reduced surface time during fall and winter and suggested this pattern may be influenced by an increase in foraging effort associated with the need to increase energy intake for the coming winter. While our study did not specifically collect data on surface bout duration, observers did note anecdotally that porpoises seemed to come to the surface less often in fall, which would decrease detection probability. If, in addition to spending less time at the surface, they were also making larger movements between these brief surfacing bouts, it could also make it harder to reliably match sightings across platforms than in other seasons. Another factor that contributed to the high fall abundance estimate was an apparent change in the spatial distribution of sightings. Porpoises were generally dispersed more along the transects in fall relative to other seasons, when they tended to occur in more localized clusters. This increased the number of distinct sightings at greater distances from the vessel in fall. Distance estimation error increased with true distance from the vessel in the calibration experiments (Table S1), which could also make it more difficult to successfully match the same sighting across platforms. Finally, 2 of the largest sighting days of any survey occurred in early fall, for both harbor porpoises and pinnipeds. In addition to some of the highest rates of harbor porpoise detections, pinniped sightings were 3 times greater than any other surveys throughout the year. The sheer volume of sightings made data recording uniquely challenging for observers on these days. Thus, while we feel the high abundance estimate for harbor porpoises in fall in this study was at least partly a reflection of truly high numbers, this estimate was potentially influenced by changes in behavior and distribution and the challenges of collecting sighting data under these circumstances. Repeating these surveys while ignoring all pinniped sightings would likely improve estimates.

Peak seasonal presence in Hood Canal likely aligns with prey availability. In other regions, harbor porpoises have been documented ingesting large prey (Fontaine et al. 1994, Aarefjord et al. 1996, Víkingsson et al. 2003, Sveegaard et al. 2012, Andreasen et al. 2017). In Washington waters, the harbor porpoise's diverse, generalist diet ranges from small schooling to larger fish such as salmonids (Walker et al. 1998, Elliser and Hall 2021). Although harbor porpoises were only observed chasing and catching and not ingesting salmon during presumed foraging activity (Elliser et al. 2020), 5 passive integrated transponder tags and 91 coded wire tags from juvenile Chinook salmon were recovered from a stranded porpoise on the southwestern Washington coast (D'Alessandro and Duffield 2019). The late summer to early fall corresponds with salmon migration in Puget Sound and Hood Canal (National Marine Fisheries Service 2016). Whether harbor porpoises may be targeting salmon or other prey in this food web, the salmon's arrival could explain the increase in porpoise abundance, changes in their distribution, and the observed apparent reduction in surface time as foraging intensifies.

These abundance estimates are markedly higher than the estimated 185 individuals (95% CI = 116–291; pooled across 3 seasons) in Hood Canal by Jefferson et al. (2016). While winter estimates were not obtained during these prior surveys because of inclement weather, even our low winter estimate (308 individuals, 95% CI = 189–305) was higher. Our estimates further suggest that the current number of porpoises in Hood Canal in fall are approximately an order of magnitude higher than those estimated by Jefferson et al. (2016). Some of these differences may be influenced by the different sampling methods (e.g., aerial vs. vessel surveys). Aerial surveys are widely used to estimate abundance of cetaceans, including harbor porpoises. Because of the speed of travel, the proportion of animals missed by an observer (perception bias) in an aerial platform is relatively high; Laake et al. (1997) estimated this proportion ranged from about 20–80% of porpoise groups depending on the experience of the observer. In addition, groups of animals are missed because they are submerged (availability bias) for the entire time an airplane passes over. Jefferson et al. (2016) applied a correction factor developed for harbor porpoises by Laake et al. (1997) to account for both perception and availability bias. Correction factors are often observer-specific and may vary regionally, temporarily, or with the behavior of the animals. If that is the case, the correction factor developed by Laake et al. (1997) may not be appropriate for other aerial surveys, and its use could potentially bias resulting estimates in ways that may not be easy to quantify. Searching for porpoises from a slower surface platform, such as the vessel used in this study, minimizes availability bias because porpoise groups are more likely to surface at least once in the observer field of view given the rate of travel of the vessel and typical porpoise dive times. In addition, our double-platform approach allowed us to estimate survey-specific perception bias, helping to ensure our estimates were as accurate as possible.

The large discrepancies between our abundance estimates and those of Jefferson et al. (2016) may also reflect true differences in densities in porpoises over the period, if the increases in harbor porpoises elsewhere in the Salish Sea continued in recent decades (Evenson et al. 2016, Jefferson et al. 2016). Harbor porpoises were one of the most commonly sighted cetaceans in the Salish Sea in the 1940s but declined dramatically by the 1970s and were essentially absent from Puget Sound (Scheffer and Slipp 1948, Flaherty and Stark 1982, Calambokidis and Baird 1994, Osmek et al. 1995, Baird 2003). Fishery interaction, pollution, and habitat degradation, among other factors, may have contributed to this decline (Scheffer and Slipp 1948, Osmek et al. 1997, Evenson et al. 2016, Jefferson et al. 2016, Elliser and Hall 2021). Fisheries and pollution were known threats within the southern Salish Sea during this decline (Evenson et al. 2016). The enactment of regulatory changes in tribal and commercial salmon and other net-based fisheries appear to align with an increase in harbor porpoise numbers, providing evidence for causality (Washington Department of Fish and Wildlife 2015, Jefferson et al. 2016). Contaminants associated with the urban development in the lower Salish Sea and the subsequent effects it may have had on the harbor porpoises and their prey followed by legislative changes to clean up Puget Sound provides another plausible link (Jefferson et al. 2016). Today harbor porpoises are present year-round in much of this region (Hall 2004, Jefferson et al. 2016, Elliser et al. 2018), with seasonal fluctuations in several areas where fine-scale local assessments have been made (Hall 2004). This includes the central Salish Sea, the waters into which Hood Canal opens, where porpoise abundance increases from spring through fall and decreases over the winter much as it did in the present study. In contrast, harbor porpoises were most likely to be observed from September through February than in summer <50 km to the northeast near Fidalgo Island, Washington (Elliser et al. 2018). Local changes in seasonal abundance observed in recent years may be regional shifts in preferred habitat throughout the Salish Sea. It is also possible that the influx of animals into Hood Canal from the greater Salish Sea varies annually and that regional habitat suitability was more favorable in 2022–2023 when compared to the mid-2010s. Additional studies are needed to better understand movement dynamics, habitat use, and trends of harbor porpoises in Hood Canal and the Salish Sea. The fact that harbor porpoises continue to occupy Hood Canal in numbers greater than observed in Jefferson et al. (2016) should provide us all with optimism when tackling conservation issues in this increasingly complex world.

MANAGEMENT IMPLICATIONS

Our work suggests the number of harbor porpoises in Hood Canal is considerably higher than the estimates upon which authorized takes in the Navy's permit were based, and that permitted activities with the potential to disturb porpoises may affect a considerably larger portion of the Washington Inland Waters stock than previously thought. This would be particularly true for activities that occur in late summer and fall when porpoise densities are at their highest in and around the DBRC. The considerable annual fluctuations in porpoise occurrence in the canal also offer a potential means of mitigating these effects, if the most disturbing activities can be preferentially scheduled during winter and early spring, when porpoise densities are at their lowest.

Unfortunately, the same seasonal fluctuations also create a less avoidable conflict with fisheries in fall, as recreational, commercial, and tribal fisherman move into Hood Canal to pursue salmonids alongside porpoises. The lack of porpoise sightings in the waters adjacent to the Naval Base Kitsap Bangor, at the center of what otherwise appears to be preferred porpoise habitat in Hood Canal, may also represent a year-round effect that is currently unknown and thus unmitigated. It presents a unique opportunity for directed research into the acoustic environment of the base, the sources of chronic noise in the frequency range to which porpoise are most sensitive, and noise management if noise is correlated with porpoise absence. Given the extensive gaps in harbor porpoise research and the changing environment of today, multi-year, fine-scale, localized studies, especially where baseline data now exist, will be key to understanding the broader spatial and temporal patterns of harbor porpoises within the canal, and managing anthropogenic effects on harbor porpoises throughout the Salish Sea.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

This work was conducted under National Marine Fisheries Service permit number 21163 and Marine Ecology and Telemetry Research Institutional Animal Care and Use protocols METR-AUP-2019-01 and METR-AUP-2022-01.

DATA AVAILABILITY STATEMENT

These data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting material may be found in the online version of this article at the publisher's website.

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