Fall through spring 2018/2019 Marbled Murrelet At-Sea Densities In Five Strata Associated with U.S. Navy Facilities in Washington State: Annual Research Progress Report 2019

Washington Department of Fish and Wildlife

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Deliverable under contract: N62473-17-2-0007

Recommended Citation:

Pearson, S.F. and M.M. Lance. 2019. Fall-spring 2018/2019 Marbled Murrelet At-Sea Densities for Four Strata Associated with U.S. Navy Facilities: Annual Research Progress Report. Washington Department of Fish and Wildlife, Wildlife Science Division, Olympia, WA.

This report is being prepared for the U.S. Navy under the NAVFAC NW Cooperative Agreement N62473-17-2-0007

INTRODUCTION

The goal of this project is to estimate on-the-water marbled murrelet (*Brachyramphus marmoratus*) densities during the fall-spring seasons (September - April) adjacent to the following facilities: (1) Naval Air Station Whidbey Island (Crescent Harbor); (2) Manchester Fuel Department; (3) Naval Base Kitsap at Bangor, Zelatched Point, Toandos, Keyport and Bremerton; (4) Naval Magazine Indian Island; and (5) Naval Station Everett. These surveys have been conducted annually since September of 2012 and, now that we have seven years of survey effort, we can begin to examine murrelet trends during the non-breeding season. Because the nearshore marine environment and murrelet densities adjacent to any one of these facilities is too small to derive reliable site-specific at-sea murrelet densities, Washington Department of Fish and Wildlife (WDFW) used a stratified sampling approach outlined in Pearson and Lance (2012, updated 31 October 2013) to derive stratum specific density estimates. This approach uses line-transect or distance sampling methods (Buckland et al. 1993) to derive murrelet density estimates for four strata using nearshore and offshore transects placed in 32 primary sampling units (PSUs) (Figure 1). Note that the coastal unit (Pacific Beach) was not surveyed this year.

METHODS

We (WDFW) used the approach and methods from the survey effort described by Raphael et al. (2007) and Miller et al. (2012) and modified by Pearson and Lance (2012; updated 31 October 2013). We use this approach because: (1) it addresses issues of detectability, (2) it is customized to murrelet distributions and densities in this region, (3) it uses pre-survey information to develop the sampling design, (4) the methodology was peer reviewed (e.g., Raphael et al. 2007, Miller et al. 2012), and because (5) we wanted our survey effort for this project to be consistent with the spring/summer murrelet monitoring effort funded by USFWS, which will ultimately allow us to compare estimates for the same sampling units among seasons.

Sampling Design and Survey Effort

The survey design that follows is described in detail in Pearson and Lance (2012, updated 31 October 2013). Thirty-five primary sampling units (PSUs) were split among 5 strata (see Figure 1 and Table 1). To derive strata and PSUs, we segmented the entire coastline of Puget Sound into 20-km Primary Sampling Units (PSUs) within Puget Sound and on the outer coast adjacent to NAVFAC NW Pacific Beach. We then combined PSUs into appropriate management/ecological/density strata (Figure 1). The area adjacent to Pacific Beach was defined as Stratum #1 (n = 3 PSUs) but this unit was not surveyed this year.

Using this information, Puget Sound strata are depicted in Figure 2 and defined as follows:

- Stratum #2 Admiralty Inlet (8 PSUs): west side of Whidbey Island Naval Air Station, Admiralty Inlet and Naval Magazine Indian Island;
- Stratum #3 North Hood Canal (7 PSUs): Bangor, Zelatched Point, Toandos, and Dabob Bay;
- Stratum #4 Whidbey Basin (11 PSUs): Crescent Harbor by Naval Air Station Whidbey Island and Naval Station Everett;
- Stratum #5 Central Puget Sound (6 PSUs): Bremerton, Manchester, Keyport

Average PSU area depicted in Figure 1 was 38.2 km^2 and covered about 20 km of shoreline. The average transect length per PSU was 34.5 km, divided between a nearshore segment (average length = 20.4 km) and an offshore segment (average length = 14.7 km) with more effort (more transect traveled) in the nearshore where murrelet densities are higher (Miller et al. 2006, Raphael et al. 2007). We used PSU numbers from the Marbled Murrelet Effectiveness Monitoring Program (Raphael et al. 2007) in order to make comparisons, if needed, with spring/summer derived encounter rates for these same PSUs. The Effectiveness Monitoring effort uses a similar survey design to this Navy effort but, because the area of interest is much larger in the Effectiveness Monitoring Program and the goals differ between these efforts, the geographic definitions of the strata are very different between programs, but the geographic boundaries of the PSUs and their numbers are identical (Raphael et al. 2007). Although the Effectiveness Monitoring Program did not include a PSU in Dyes Inlet, the Navy requested this area be sampled. As a result, a new PSU was created and labeled "900" to avoid any confusion with those PSUs already established.

We conducted four replicate surveys of all PSUs in Strata 2-5 as follows:

Fall = 10 September - 20 November 2018
Late Fall/Early Winter = 14 November 2018 – 11 January 2019
Winter = 11 January – 28 February 2019
Early Spring = 5 March – 16 April 2019

The survey date for each PSU and overall survey schedule is provided in Table 1. To derive this schedule, we randomly selected a Strata first. Within Strata, we then randomly selected the order of the Core PSUs (those adjacent to Navy facilities) and surveyed them prior to surveying the remainder of the PSUs in a Strata to make sure that we surveyed those important PSUs in each replicate should bad weather/sea conditions prevent us from surveying all PSUs. We also randomly determined whether we surveyed the nearshore or offshore segments first. There were often Naval activities in Dabob Bay which prevented us from surveying on the dates selected by this process. As a result, we coordinated closely with range officers to alter our schedule as necessary.

Observer Training

The team consisted of four observers/data recorders and a rotating boat operator (but a designated Captain). The data recorder and two observers (one responsible for each side of the boat) switched duties at the beginning of each primary sampling unit (PSU) to avoid survey fatigue. All of the observers had considerable experience monitoring seabirds at sea and work on surveys nearly year-round. All of the observers had completed our one week of training at least once and most twice because the training is annual. Office training included a presentation of background information, survey design and protocols, sampling methodology, line transect distance sampling methodology, and measurement quality objectives. On-water training included boat safety orientation, seabird identification, specific training on correctly assigning marbled murrelet plumages (Strong 1998), conducting transect surveys, and distance estimation testing using laser rangefinders. Boat safety training included instructions and reminders for weather and sea condition assessment, use of the radio, boat handling, proper boat maintenance, safety gear, rescue techniques, and emergency procedures. Observer training was designed to be consistent with training conducted by other groups within the Marbled Murrelet Effectiveness Monitoring Program (Raphael et al. 2007, Huff et al. 2003, Mack et al. 2003).

During practice transects, observers were taught how to scan, where to focus their eyes, and which portions of the scan area are most important. Distance estimates from the transect line are a critical part of the data collected and substantial time was spent practicing and visually 'calibrating' before surveys began. During distance trials, each individual's estimate of perpendicular distance was compared to a perpendicular distance recorded with a laser rangefinder. These trials were conducted using stationary buoys and bird decoys as targets, which were selected at a range of distances from the transect line and in locations in front of as well as to the sides of the boat where marbled murrelets would be encountered on real surveys (Raphael et al. 2007). Each observer completed 100 distance estimates during pre-survey training and was tested weekly. For the weekly tests, each observer estimated five perpendicular distances to floating targets and the actual perpendicular distance was measured with a laser rangefinder. After the first set of five, the observer's results were assessed. If all five estimates were within 15% of the actual distance, the trial was complete for that observer. If any of the five estimates were not within 15% of actual, the observer continued to conduct estimates in sets of five until all five distances were within 15% of the actual distance. In addition, one of the project leads accompanied the survey crew and observed their overall performance and ability to detect marbled murrelets during the survey season and completed an audit form created by the Murrelet Monitoring Program (Raphael et al. 2007). The results of the audit were shared with the observers after the survey day was completed for feedback and discussion.

Field Methods and Equipment

Two observers (one on each side of the boat) scanned from 0° off the bow to 90° abeam of the vessel. More effort was spent watching for marbled murrelets close to the transect line ahead of the boat (within 45° of line). Observers scanned continuously, not staring in one direction, with a complete scan taking about 4-8 seconds. Observers were instructed to scan far ahead of the boat for birds that flush in response to the boat and communicate between observers to minimize missed detections. Binoculars were used for species verification, but not for sighting birds. For each marbled murrelet sighting the following data were collected: group size (a collection of birds separated by less than or equal to 2 m at first detection and moving together, or if greater than 2 m the birds are exhibiting behavior reflective of birds traveling and foraging together and therefore not independent), plumage class (Strong 1998), and water depth (from boat depth finder).

Observers relayed data (species, number of birds, estimated perpendicular distance of the bird(s) from the trackline) via headsets to a person in the boat cabin who entered data directly onto a laptop computer with software (DLOG3 developed by R.G. Ford, Inc., Portland, OR.) that is interfaced with a GPS unit and collects real time location data. DLOG3 interfaces with a handheld GPS and GIS overlays of the Washington shoreline and adjacent bathymetry, and uses these data to record GPS coordinates and perpendicular distance to shore at operator-defined time intervals (e.g. every 30 seconds). Transect survey length was calculated from the GPS trackline recorded in

DLOG3. Additional data such as PSU identification, weather and sea conditions, on/off effort, and names of observers were typed into the DLOG3 program on the computer during the survey.

The team used the 26-foot Lee Shore (Research Vesssel Fog Lark) with twin-outboard engines. Survey speed was maintained at 8-12 knots, and survey effort was ended if glare obstructed ≥ 30-40% of a given surveyors view (code = 3), or if Beaufort wind scale was 3 or greater. Beaufort 3 is described as a gentle breeze, 7-10 knot winds, creating large wavelets, crests beginning to break, and scattered whitecaps (Beaufort scale is provided in Appendix I).

Data Analysis

We used transect distances, murrelet group size, and perpendicular distances for each marbled murrelet observation to derive density (birds/km^2) estimates by stratum using the program DISTANCE. For details about our analysis approach, see Miller et al. (2006) and Raphael et al. (2007). Briefly, the Distance or line transect survey approach requires observers to move along a fixed path (transect) and to count occurrences of the target animal (marbled murrelet) along the transect and, at the same time, obtain the distance of the object from the transect. This information, is then used to estimate the area covered by the survey and to derive an estimate of the way in which detectability increases from probability 0 (far from the transect) towards 1 (near the transect). The shape of this detectability function can then be used in conjunction with the counts, distances to the birds, and the distance traveled (transect length) to derive an estimate of Density (birds/km^2). For details, please see Buckland et al. (1993). In the Results, we provide murrelet density estimates by Strata for each of the sampling periods (see above) and across all sampling periods (global model). The density provided can be viewed as the murrelet population on the water on a given day within the area and time period defined.

RESULTS/DISCUSSION

During the Fall-Spring 2018/2019 season, we surveyed 4,251 km of transects and detected 644 murrelets during those surveys. Because these were replicated surveys, these are not all unique individuals. All 32 PSUs were sampled during each of the four "seasons" as planned.

When examining density estimates by stratum (Table 2), higher densities were consistently found in Stratum 2 except for the Fall (Nov - mid-Jan) when densities were higher in Stratum 3. Highest densities in the Puget Sound region occurred in the Winter (mid-Jan - Feb). As in past years, Murrelet densities were very low to no birds in Stratum 5, generally intermediate in Strata 3 and 4, and highest in Stratum 2.

Using overall densities across all four replicates and all four strata, we estimated there 631murrelets (95% CI = 415-960) in all Puget Sound strata (Sept – April), which is the lowest density estimate in the seven years of sampling (see Figure 2: "Puget Sound" graph). There was some seasonal variation in our all Puget Sound estimate with relatively few birds detected during the early fall and spring sampling periods (Table 2).

In Figure 2, we compare densities among strata and years. Across all seven years, there is some variability among years, but it appears that murrelets are declining for all Strata combined. At the stratum level, there appears to be a declining trend in the Admiralty Inlet strata and in Hood Canal. As in previous years, this graph emphasizes the high murrelet density and considerable variability in density in Admiralty inlet. This is an area of strong currents driven by large tidal exchanges, which may influence the availability of forage fish depending on the time of day and the phase of the moon. This is paticularly true if birds are moving between the south side of Point Wilson (currently sampled) and the north and West (currently not sampled). This suggests the need to add an additional PSU to the West of Point Wilson to help us understand this variability.

Although we cannot derive PSU scale density estimates because they represent a single sample and because relatively few birds are encountered within a PSU (also high variability at that spatial scale), we can qualitatively explore encounter rates (# murrelets encountered per kilometer of transect length sampled; Table 3) by PSU. As in previous years, the PSUs on the western side of Admiralty Inlet had relatively high murrelet encounter rates (Table 3, especially PSU 30) with high densities in the area spanning from Point Wilson southward through Port Townsend Bay. The west side of Hood Canal near Bangor had relatively high murrelet encounter rates and so did the PSUs near Everett and Crescent Harbor. Unusual for this seven year data set was the high detection of birds in the fall along the east side of Bainbridge Island. Again, some PSUs have no to few detections and some, like the Bainbridge Island PSU, have high densities in a single season. This variation in density over time and space suggests movement of birds tracking food resources throughout the larger region. As in previous years, Stratum 5 had very few to no birds, which supports the poor availability of forage fish in south to central Puget Sound (Rice et al. 2012, Greene et al. 2015).

The variability that we are seeing within a given PSU (and within a stratum) throughout the fall/winter period suggests some movement of birds within the study area and perhaps in and out of the study area. Again, because birds can move large distances during our sampling effort, there may be considerable variation in encounter rates among seasons and years at this spatial scale.

With six years of data (2013-2019) from the Puget Sound region, we can now start to think about assesing population trends. When examining a potential linear trend over this time period, there is strong evidence for a 16.42% annual decline in the Puget Sound wintering population (p = 0.032, r^2 = 0.66; Figure 2 - *Puget Sound*). During this period of Navy funded survey work, the density of murrelets has decreased from a high of 2.21 birds per km^2 (95% CI = 1.52-3.21%) during the winter of 2012/2013 to the current low of 0.67 birds per km^2 (95% CI = 0.44-1.02%) during the winter of 2018/2019 (Figure 2 - *Puget Sound*), this represents a 60% decline in the wintering murrelet population.

There are now several independent efforts indicating that the murrelet population in the U.S. portion of the Salish Sea (Puget Sound, San Juan Archipelago, and Strait of Juan de Fuca) is declining. The long-term monitoring effort Northwest Forest Plan Effectiveness Monitoring Program indicates a 4.9 percent annual decline for the 2001-2018 period (McIver et al. 2019). This spring/ summer effort uses the identical line transect survey methodology reported here and some of the same primary sampling units. Similarly, Lorenz and Raphael (2018) found the murrelet populations in the San Juan Islands (the region of the Salish Sea with highest murrelet densities) to have declined from 11.16 to 5.76 murrelets km^2 between 1995 and 2012. Despite this consistent and ominous decline in overall murrelet density, they found that the density of juvenile murrelets and murrelet productivity ratio (juveniles:adults) did not decline over this time period (Lorenz and Raphael 2018). They concluded that the declining density of murrelets in the San Juan Islands was due to declines in adult murrelets only, not juveniles. Interestingly, the annual estimates of overall murrelet density were positively correlated with winter El Niño Southern Oscillation (ENSO) indices (Lorenz and Raphael 2018). In ENSO years, numbers increased dramatically suggesting that the Salish Sea may provide a refugia marine habitat for murrelets when prey availability along the outer Pacific Coast is poorer than usual (Lorenz and Raphael 2018).

Conclusions

- With seven years of Navy-funded survey effort during the non-breeding season, we can now describe for the first time non-breeding murrelet trends in Puget Sound.
- In addition, we are getting a better understanding of the year-to-year variability in murrelet abundance during the non-breeding season.
- Three independent survey efforts (two breeding season surveys and this non-breeding season survey) all indicate long-term and precipitous murrelet declines in Puget Sound and, more broadly, in the Salish Sea.
- Our next step is to summarize all of the Navy-funded murrelet survey results for this region and compre those results to other surveys to more formally examine how murrelet populations are changing seasonally. This work will be compiled into a manuscript for publication in the peer-reviewed literature.
- We recommend using hierarchichal distance survey models to: (1) examine both the marine and terrestrial factors responsible for murrelet declines, and (2) build maps that help us understand hotspots of murrelet abundance and how those hot (and cold) spots vary among seasons.

ACKNOWLEDGEMENTS

This survey effort, design and analysis were funded by the U.S. Navy. We thank Cindi Kunz for her excellent help with all stages of this work. A special thank you to Chad Norris our boat captain and biologists Kelly Beach, Caanan Cowles, and Jessica Stocking. We thank C. Kunz for reviewing an earlier draft of this report.

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Figure 1. Stratum and primary sampling unit locations in Puget Sound. Strata are defined in the figure Key and PSUs are numbered on the map. Note that Stratum #1 was not sampled this year and is not pictured below.

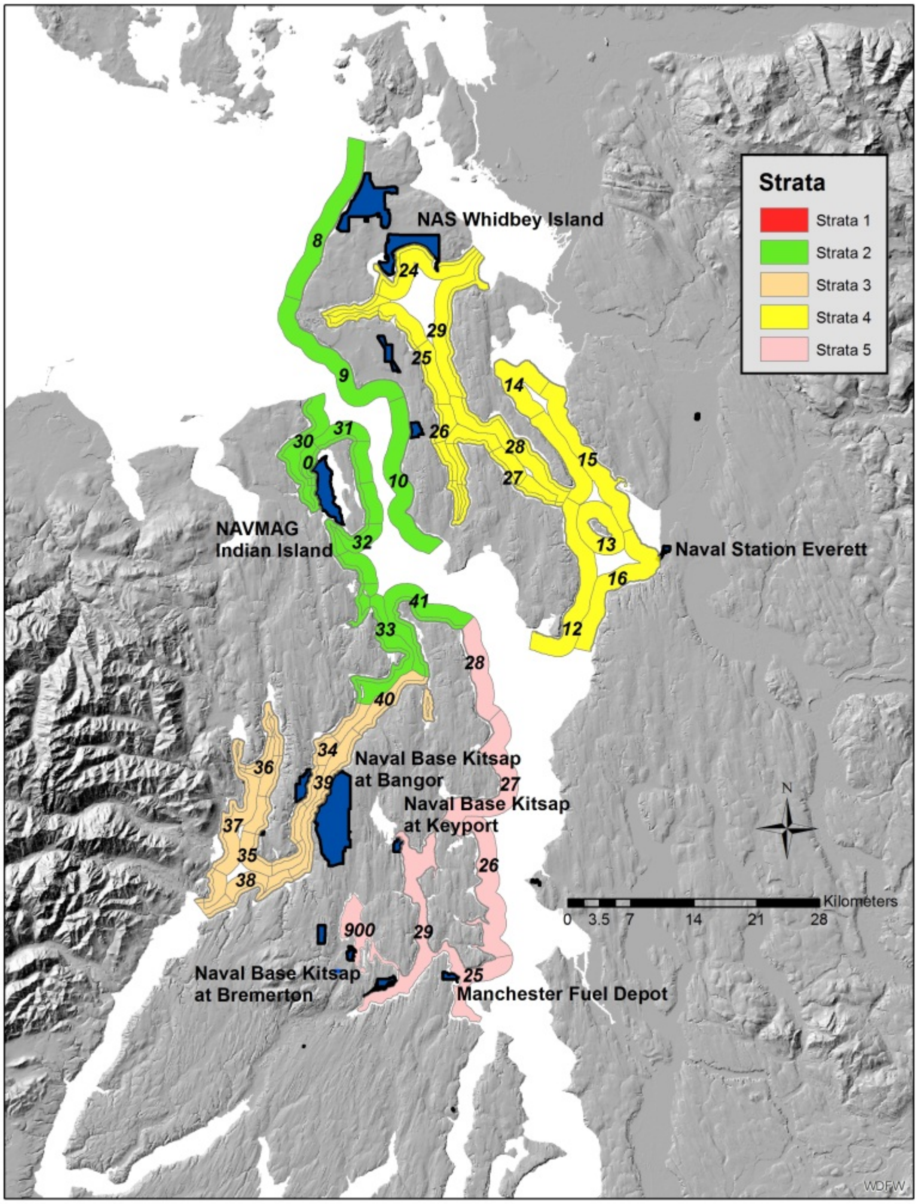

Figure 2. Density of marbled murrelets (± 95% CI) in the entire Puget Sound study area (Strata 2-5 combined) and by individual strata. Geographic location of each stratum is provided in Figure 1.

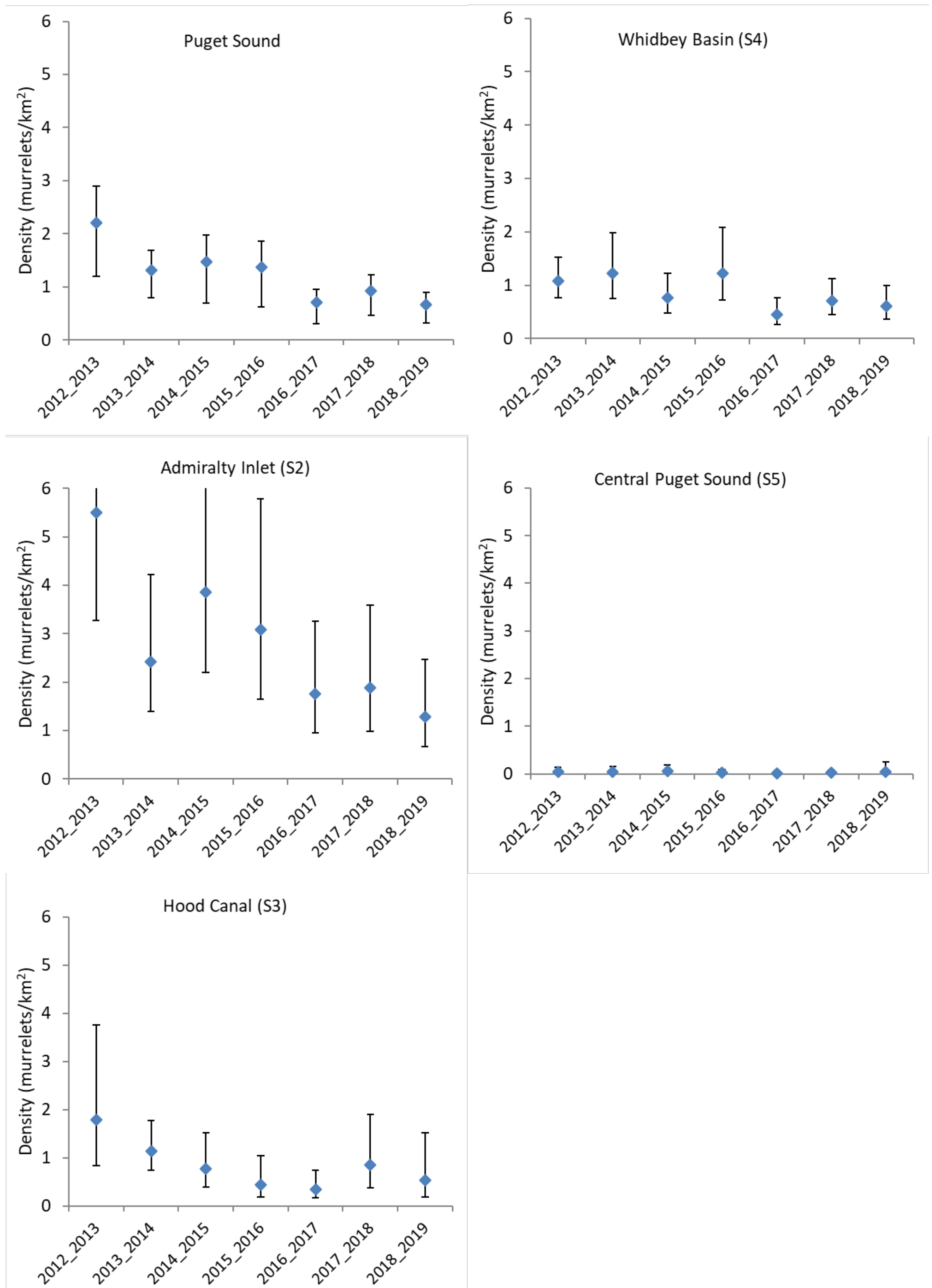

Table 1. Dates of Primary sampling unit (PSU) surveys by sampling season: Early fall = mid-Sept – Nov; Fall = Nov - mid-Jan; Winter = mid-Jan - Feb; Spring = Mar – mid-Apr. Primary sampling units adjacent to Naval facilities are in bold and highlighted. Geographic locations of each PSU can be determined by first identifying the Stratum number and then the PSU in Figure 1.

Stratum	PSU	Early Fall	Fall	Winter	Spring
2	**8**	14-Sep	5-Dec	11-Jan	5-Mar
	9	24-Oct	5-Dec	11-Jan	29-Mar
	10	24-Oct	11-Jan	28-Feb	8-Mar
	30	10-Oct	28-Nov	14-Jan	5-Mar
	31	10-Oct	5-Dec	14-Jan	29-Mar
	32	14-Sep	8-Jan	6-Feb	13-Mar
	33	26-Oct	8-Jan	6-Feb	13-Mar
	41	24-Oct	7-Jan	19-Feb	8-Mar
3	34	11-Oct	15-Dec	24-Jan	25-Mar
	35	5-Oct	12-Dec	20-Feb	18-Mar
	36	12-Sep	30-Nov	31-Jan	18-Mar
	37	5-Oct	21-Dec	31-Jan	18-Mar
	38	12-Sep	21-Dec	24-Jan	6-Mar
	39	11-Oct	15-Dec	24-Jan	6-Mar
	40	26-Oct	30-Nov	19-Feb	25-Mar
4	12	30-Oct	6-Dec	28-Feb	19-Mar
	13	30-Oct	6-Dec	7-Feb	16-Apr
	14	5-Nov	4-Dec	30-Jan	16-Apr
	15	4-Oct	4-Dec	30-Jan	19-Mar
	16	4-Oct	4-Dec	30-Jan	19-Mar
	24	18-Oct	29-Nov	15-Jan	15-Mar
	25	1-Nov	29-Nov	16-Jan	15-Mar
	26	18-Oct	29-Nov	16-Jan	4-Apr
	27	18-Oct	10-Dec	7-Feb	8-Apr
	28	5-Nov	10-Dec	7-Feb	8-Apr
	29	1-Nov	6-Dec	15-Jan	4-Apr
5	**25**	17-Oct	19-Dec	21-Feb	28-Mar
	26	17-Oct	19-Dec	21-Feb	28-Mar
	27	20-Nov	7-Jan	27-Feb	12-Apr
	28	20-Nov	7-Jan	27-Feb	12-Apr
	29	9-Oct	14-Nov	29-Jan	14-Mar
	900	10-Sep	14-Nov	29-Jan	14-Mar

Table 2. Estimates of marbled murrelet density (birds/km^2) and population size by sampling season (and all seasons combined = global model) for four Puget Sound Strata, and all Puget Sound strata combined. Strata are defined in Figure 1. Birds were only detected in Stratum 5 in the Fall and Early Spring sampling periods.

Year	Stratum	Density (birds /km^2	StdErr	%CV	Birds	Birds 95% CL Lower	Birds 95% CL Upper	Area (km^2)	f(0)	Std. Err. Of f(0)	E(s)	Std. Err. Of E(s)	Truncation Distance
All sampling periods combined – Early Fall through Early Spring (mid-Sept – late-Apr)													
2018/2019	**All**	**0.670**		**21.27**	**631**	**415**	**960**	**942.0**	**0.009**	**0.000**	**1.937**	**0.040**	**211**
2018/2019	2	1.286	0.423	32.93	**330**	172	634	256.7					
2018/2019	3	0.533	0.291	54.73	**87**	30	247	162.5					
2018/2019	4	0.599	0.154	25.75	**207**	124	344	345.1					
2018/2019	5	0.044	0.045	101.83	**8**	1	45	177.6					
Early Fall (mid-Sept – Nov)													
2018	**All**	**0.444**		**30.81**	**418**	**220**	**794**	**942.0**	**0.010**	**0.001**	**1.841**	**0.094**	**211**
2018	2	1.048	0.417	39.83	269	111	651	256.7					
2018	3	0.0321	0.0319	5.10	5	1	39	162.5					
2018	4	0.4178	0.1881	45.04	144	56	371	345.1					
2018	5	0			0			177.6					
Fall (Nov - mid-Jan)													
2017	**All**	**0.681**		**34.52**	**642**	**316**	**1303**	**942.0**	0.010	0.001	**1.766**	**0.055**	**211**
2017	2	0.491	0.235	47.89	**126**	43	367	256.7					
2017	3	1.366	0.981	71.81	**222**	46	1070	162.5					
2017	4	0.851	0.399	46.97	**294**	109	791	345.1					
2017	5	0			**0**			177.6					
Winter (mid-Jan - Feb)													
2018	**All**	**1.176**		**41.34**	**1108**	**449**	**2734**	**942.0**	**0.010**	**0.001**	**1.971**	**0.055**	**211**
2018	2	2.842	1.70	59.90	**730**	199	2679	256.7					
2018	3	0.342	0.186	54.38	**56**	16	191	162.5					
2018	4	0.832	0.327	39.30	**287**	124	662	345.1					
2018	5	0.198	0.213	107.5	**35**	4	333	177.6					
Spring (Mar – mid-Apr)													
2018	**All**	**0.207**		**39.63**	195	**86**	**442**	**942.0**	**0.006**	**0.001**	**1.889**	**0.066**	**211**
2018	2	0.506	0.267	52.79	**130**	42	400	256.7					
2018	3	0.164	0.118	72.28	**27**	6	124	162.5					
2018	4	0.111	0.050	45.40	**38**	15	97	345.1					
2018	5	0			**0**			177.6					

Table 3. September – April marbled murrelet encounter rate (# birds detected/km transect length sampled) by primary sampling unit.   Primary sampling units adjacent to Naval facilities are in bold and highlighted. Sampling seasons: Early fall = mid-Sept – Nov; Fall = Nov - mid-Jan; Winter = mid-Jan - Feb; Spring = Mar – mid-Apr. Geographic locations of each PSU can be determined by first identifying the Stratum number and then the PSU in Figure 1.

Stratum	PSU	Early Fall	Fall	Winter	Spring	Average
2	**8**	0.520	0.056	0.000	0.058	0.159
	9	0.000	0.149	0.000	0.088	0.059
	10	0.000	0.000	0.000	0.374	0.094
	30	1.020	0.116	0.029	0.000	0.291
	31	0.304	0.029	0.000	0.058	0.098
	32	0.579	0.000	0.000	0.000	0.145
	33	0.148	0.000	0.000	0.055	0.051
	41	0.000	0.029	0.261	0.000	0.073
3	34	0.029	1.084	0.469	0.000	0.396
	35	0.000	0.194	0.560	0.150	0.226
	36	0.000	0.000	0.000	0.000	0.000
	37	0.000	0.000	0.000	0.000	0.000
	38	0.000	0.000	0.000	0.000	0.000
	39	0.000	0.059	0.177	0.000	0.059
	40	0.000	0.000	0.000	0.057	0.014
4	12	0.000	0.145	0.088	0.000	0.058
	13	0.000	0.000	0.339	0.085	0.106
	14	0.000	0.571	0.055	0.000	0.157
	15	0.000	0.000	0.000	0.000	0.000
	16	0.000	0.543	1.486	0.606	0.659
	24	0.399	0.070	3.416	0.175	1.015
	25	0.143	0.214	0.362	0.000	0.180
	26	0.000	0.000	0.062	0.000	0.016
	27	0.000	0.000	0.174	0.315	0.122
	28	0.316	0.000	0.000	0.000	0.079
	29	0.471	0.000	0.000	0.000	0.118
5	**25**	0.000	0.378	0.000	0.000	0.094
	26	0.000	1.693	0.234	0.000	0.482
	27	0.000	0.174	0.059	0.000	0.058
	28	0.000	0.037	0.000	0.144	0.045
	29	0.000	0.000	0.059	0.000	0.015
	900	0.000	0.000	0.000	0.000	0.000

Appendix I

BEAUFORT WIND SCALE WITH CORRESPONDING SEA STATE CODES					
Beaufort Number	Wind Velocity (Knots)	Wind Description	Sea State Description	Sea State	
				Term and Height of Waves (Feet)	Condition Number
0	Less than1	Calm	Sea surface smooth and mirror-like	Calm, glassy 0	0
1	1-3	Light Air	Scaly ripples, no foam crests		
2	4-6	Light Breeze	Small wavelets, crests glassy, no breaking	Calm, rippled 0 – 0.3	1
3	7-10	Gentle Breeze	Large wavelets, crests begin to break, scattered whitecaps	Smooth, wavelets 0.3-1	2
4	11-16	Moderate Breeze	Small waves, becoming longer, numerous whitecaps	Slight 1-4	3
5	17-21	Fresh Breeze	Moderate waves, taking longer form, many whitecaps, some spray	Moderate 4-8	4
6	22-27	Strong Breeze	Larger waves, whitecaps common, more spray	Rough 8-13	5
7	28-33	Near Gale	Sea heaps up, white foam streaks off breakers	Very rough 13-20	6
8	34-40	Gale	Moderately high, waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks		
9	41-47	Strong Gale	High waves, sea begins to roll, dense streaks of foam, spray may reduce visibility		
10	48-55	Storm	Very high waves, with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility	High 20-30	7
11	56-63	Violent Storm	Exceptionally high waves, foam patches cover sea, visibility more reduced	Very high 30-45	8
12	64 and over	Hurricane	Air filled with foam, sea completely white with driving spray, visibility greatly reduced	Phenomenal 45 and over	9

Figure 8-1. Beaufort wind scale.