Abundance of Belugas, *Delphinapterus leucas*, in Cook Inlet, Alaska, 1994–2000

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Introduction

Beluga, *Delphinapterus leucas*, abundance in Cook Inlet has been estimated by several authors in the past three decades to be in the range of 300–1300 whales (reviewed in Rugh et al., 2000). In some cases, those were the sums of maximum visual counts and therefore represent minimum estimates. In other cases, estimates of total abundance were made by multiplying the counts by ad hoc correction factors to account for whales that were presumed to have been missed. None of these earlier surveys were designed specifically to estimate total abundance of belugas in Cook Inlet, but they have provided useful information on distribution, behavior, ecology, and minimum abundance.

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ABSTRACT—Annual abundance estimates of belugas, Delphinapterus leucas*, in Cook Inlet were calculated from counts made by aerial observers and aerial video recordings. Whale group-size estimates were corrected for subsurface whales (availability bias) and whales that were at the surface but were missed (detection bias). Logistic regression was used to estimate the probability that entire groups were missed during the systematic surveys, and the results were used to calculate a correction to account for the whales in these missed groups (1.015, CV = 0.03 in 1994–98; 1.021, CV = 0.01 in 1999–2000). Calculated abundances were 653 (CV = 0.43) in 1994, 491 (CV = 0.44) in 1995, 594 (CV = 0.28) in 1996, 440 (CV = 0.14) in 1997, 347 (CV = 0.29) in 1998, 367 (CV = 0.14) in 1999, and 435 (CV = 0.23, 95% CI=279–679) in 2000. For management purposes the current N_{best} = 435 and N_{min} = 360. These estimates replace preliminary estimates of 749 for 1994 and 357 for 1999. Monte Carlo simulations indicate a 47% probability that from June 1994 to June 1998 abundance of the Cook Inlet stock of belugas was depleted by 50%. The decline appears to have stopped in 1998 .*

Drawing on the observations and insights from those studies, we designed a survey to estimate absolute abundance of Cook Inlet belugas. Accurate abundance estimates depend on:

1) Repeated systematic surveys for beluga groups throughout their known range, and counts of each group seen (Rugh et al., 2000).
2) Corrections for whales that were missed during the counts (Hobbs et al., 2000), in particular for: A) whales that never surfaced during the count (availability bias); and B) whales that surfaced but were missed during the count (detection bias).
3) Corrections for whales not counted because the entire group was not detected by observers during one or more surveys (calculated in this report).

Background

During late spring and early summer, dense aggregations of belugas are found near river mouths along the shores of upper Cook Inlet (Rugh et al., 2000). Very few belugas have been seen outside of Cook Inlet in the Gulf of Alaska (Laidre et al., 2000), and in recent years during June or July, belugas have become rare except near shore in the upper inlet (Rugh et al., 2000). Large tidal fluctuations in Cook Inlet (>10 m) and broad tidal flats (>7 km across) result in strong currents and significant changes in the shoreline through each tidal cycle. Belugas move with these tidal fluctuations to remain in fairly shallow water, perhaps to optimize feeding opportunities on fish runs (Huntington, 2000; Moore et al., 2000).

Observed behavior within a group may vary from nondirectional milling to traveling rapidly in a closely packed, unidirectional manner, to resting at the surface. Because the waters in upper Cook Inlet are extremely turbid and essentially opaque, any part of a beluga that is below the surface is out of sight. When at the surface, belugas appear as white or gray ovals against a brown background of water. The white adult whales contrast with the water, which makes them easy to see even at a distance; however, the gray color of young belugas is harder to detect. Water disturbance incurred when whales come to the surface to breathe can serve as a sighting cue, albeit a subtle one.

Field Methods

Aerial surveys were designed to take advantage of the highly aggregated population of belugas seen near river mouths and relatively good weather and visibility in June and July. Survey protocol involved systematic searches of all coastal areas (within 3 km of the waterline) around Cook Inlet (1,350 km), where virtually all belugas are found during these months, as well as flying 500 to 1,500 km of sawtooth transects across the middle of the inlet to search for whales beyond 3 km from shore (Rugh et al., 2000).

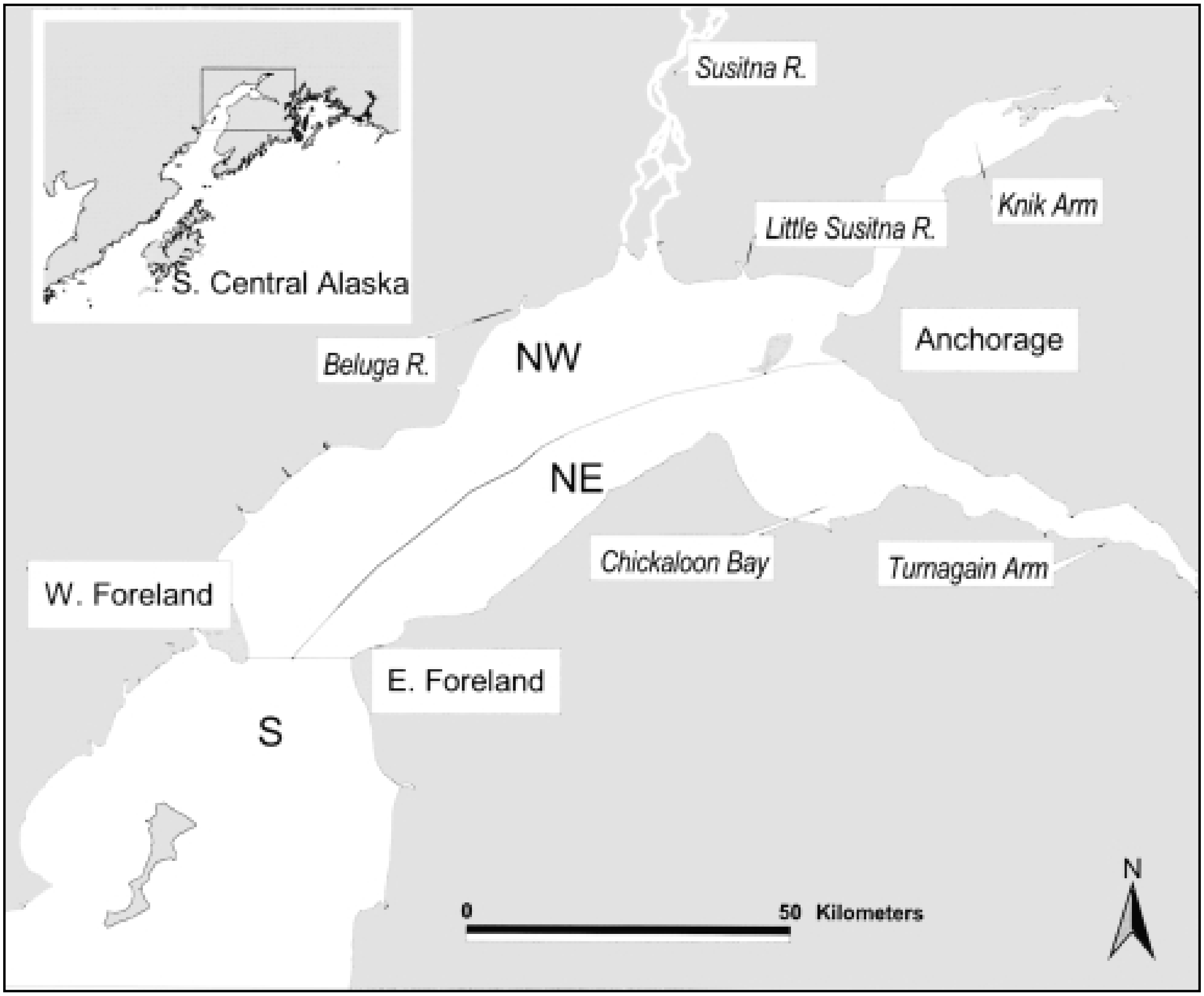

Figure 1.—Cook Inlet, in south-central Alaska, divided into three geographical sections for this report: 1) Northwest (West Foreland to Anchorage); 2) Northeast (Anchorage to East Foreland); and 3) South (lower Cook Inlet, south of the Forelands).

When possible, visual and auditory isolation was maintained between observers to allow independent search effort. This independent search was interrupted during weather checks and when circling groups. When groups were found, repeated counts were made using an extended racetrack flight pattern, such that observers always counted and video-recorded groups on the same side of the aircraft while passing them on a straight line. Generally, each observer had 4 opportunities to count each whale group encountered on each survey day.

Because the upper inlet was surveyed 2–4 times each year, there were many resightings of groups of the same whales seen on different days. To account for these resightings in the following analysis, whales in Cook Inlet were considered to be from one of three geographical sections: 1) Northwest (from West Foreland to Anchorage, including Beluga River, the Susitna Rivers, and Knik Arm); 2) Northeast (from Anchorage to East Foreland, including Turnagain Arm and Chickaloon Bay); and 3) South (anywhere south of the Forelands down to the mouth of Cook Inlet; Fig. 1). This subdivision of Cook Inlet assumed that whales may move within a section but not between sections from one survey day to the next during the survey period (3–9 days per year). Consistency in sighting locations have been evident in the multiple surveys conducted each year from 1993 to 2000 (Rugh et al., 2000) and from a whale that provided location data daily through the summer of 1999 (Ferrero et al., 2000).

Analysis Methods

Group-size estimates were available either from the analysis of video recordings or from observers' aerial counts corrected for missed whales (Table 1; Hobbs et al., 2000). Also estimated is the fraction of the total population of whales that were in groups not seen during the aerial surveys (see "Correction for Missed Groups" below). Group sizes were then summed to estimate abundance within each geographical section for each survey day. These daily abundances were averaged to estimate annual abundance in each section. Finally, the sectional abundances were summed to calculate total annual abundance.

Correction for Missed Groups

The fraction of the total population of belugas in groups that were missed during systematic surveys was estimated from the paired, independent records of primary observers on the shoreward side of the aircraft. Iterative logistic regression with an offset (Buckland et al., 1993:288–289) was used to estimate the probability of detection associated with each recorded whale group. Possible covariates were position in the aircraft (front or middle), group size, observer, sea state, and visibility.

Once the matching record was established, all covariates were examined individually as binned categorical data. Functional forms were chosen or bins were combined to represent the data with as few parameters as possible. All covariates were then entered into the model, and a backward step-wise model selection was followed until no step decreased the Akaike Information Criterion (AIC). The logistic regression model was used to estimate p_g, the probability that the gth group was detected by at least one observer:

$$p_g = 1-(1-p_{gf})(1-p_{gm}),$$

where p_{gf} and p_{gm} are the probability of detection by the front and middle observers, respectively. The correction for the fraction of whales in missed groups, $\hat{K}$, was a weighted average (Seber, 1973) of the inverse of the estimated probability of detection of each group (to account for the possibility that a group of similar size was missed) using the estimated group size for each group as the weight:

$$\hat{K}_y = \frac{\sum_{g=1}^{J_y} \frac{\hat{n}_g}{p_g}}{\sum_{g=1}^{J_y} \hat{n}_g},$$

$$CV(\hat{K}_y) = \frac{1}{\hat{K}_y}\sqrt{\frac{\sum_{g=1}^{J_y}\left[\hat{n}_g\left(\hat{K}_y-\frac{1}{p_g}\right)^2\right]}{(J_y-1)\sum_{g=1}^{J}\hat{n}_g}},$$

where J_y for y = 1994–1998, is the number of all the groups encountered in all of the surveys from 1994 to 1998, so that K_y is the same for each of the surveys in those years. For y = 1999 and 2000, J_y was the number of groups from the years 1997 to 2000, so that K_y was changed after 1998.

Abundance Estimate

The three sections of Cook Inlet (Fig. 1) were each surveyed different numbers of times each year, so it is necessary to estimate abundance in each section separately as,

$$\hat{N}_{s,y} = \frac{\hat{K}_y}{J_{s,y}}\sum_{j=1}^{J_{s,y}}\sum_{i=1}^{G_{j,s,y}}\hat{n}_{i,j}$$

$$Var(\hat{N}_{s,y}) = \frac{1}{J_{s,y}-1}\sum_{j=1}^{J_{s,y}}\left(\hat{N}_{s,y}-\hat{K}_y\sum_{i=1}^{G_{j,s,y}}\hat{n}_{i,j}\right)^2 + \frac{\hat{K}_y^2}{J_{s,y}^2}\sum_{j=1}^{J_{s,y}}\sum_{i=1}^{G_{j,s,y}}Var(\hat{n}_{i,j}) + CV^2(\hat{K}_y)\hat{N}_{s,y}^2,$$

where $\hat{N}_{s,y}$ is the estimated average abundance in section s during year y,
$G_{j,s,y}$ is the number of groups seen in section s during survey j in year y,
$J_{s,y}$ is the number of surveys conducted in section s during year y, and
$\hat{n}_{i,j}$ is the estimated number of whales in group i of survey j.

The abundance estimate for the entire inlet each year is then the sum of the abundance estimates for the three sections:

$$\hat{N}_y = \sum_{s=1}^{3}\hat{N}_{s,y},$$

$$Var(\hat{N}_y) = \sum_{s=1}^{3}Var(\hat{N}_{s,y}),$$

where $\hat{N}_y$ is the estimated average abundance in year y.

Trend in Abundance and Probability of Depletion

To test for a trend in abundance during the years when large numbers of beluga were harvested, 1994–1998 (Mahoney and Shelden, 2000), and estimate the probability that the population was depleted by 1998 (i.e. 50% of the 1994 level), a population model was fitted to the abundance estimates for those years and projected forward to 1999. The model was based on the assumptions that: 1) the per capita natural rate of increase of belugas remains constant from year to year, 2) most of the hunting-related mortality occurs in June and July and impacts males and females equally, 3) population growth occurs in the spring before the census, and 4) immigration and emigration do not occur (O'Corry-Crowe et al., 1997; Laidre et al., 2000).

Annual change in the population was then modeled as,

$$N_{y+1} = (N_y - H_y)(1+r),$$

where N_y is the abundance in year y,
H_y is the total harvest-related mortality in year y, and
r is the net per capita annual increase in the population (i.e. the difference between the birth rate and the natural mortality rate).

Two possible models were considered for annual harvest mortality: 1) harvest remained constant from year to year ($H_y = H$), and 2) harvest was a con-

Table 1.—Beluga groups reported during surveys of Cook Inlet, Alaska, 1994–2000, used to estimate abundance and/or corrections for missed groups. Groups summed for the abundance estimates are indicated in the survey and section columns. "Survey" indicates which survey within the year in which the sighting occurred and "Section" refers the section of the inlet, northwest, northeast, and south (Fig. 1) in which the sighting was located. "Estimation method" indicates whether group size was estimated from video analysis (vid.) or by correction of counts from aerial observers (obs.). "Group size" is the corrected estimate for the respective group (from Hobbs et al., 2000). The last three columns indicate sighting records used in the logistic regression to estimate the probability that a beluga group might have been missed by the aerial observers.

Date	Group	Survey	Section (Fig. 1)	Sighting location	Estimation method	Group size ($\hat{n}_g$)	CV($\hat{n}_g$)	Obs.[1]	Vis[2]	Seen[3]
6/2/94	1	1	NW	W. of Big Susitna R.	Obs.	394	0.60	3,2	G	1,1
	2	1	NE	Turnagain Arm	Obs.	18	0.47	3,2	G	0,1
	2	1	NE	Turnagain Arm	Obs.	18	0.47	3,2	G	1,1
	3	1	NE	Chickaloon Bay	Obs.	47	0.43	3,2	F	1,0
6/3/94	1			Pt. Possession	Obs.	27	0.39	4,3	G	0,1
	2	1	S	Kachemak Bay	Obs.	8	0.31	4,3	E	0,1
	3	1	S	Kachemak Bay	Obs.	13	0.29			
6/4/94	1	1	S	Iniskin Bay	Obs.	4	0.30			
	2	2	NW	W. of Big Susitna R.	Obs.	144	0.31	3,1	G	0,1
	3	2	NW	Big Susitna R.	Vid.	252	0.22	3,1	G	1,1
	4	2	NW	W. of Little Susitna R.	Vid.	475	0.24	3,1	G	1,1
6/5/94	1	3	NE	Pt. Possession/E. Foreland	Obs.	2	0.93	2,3	F	0,1
	2	3	NW	Beluga R.	Vid.	41	0.51	2,3	G	1,0
	3	3	NW	W. of Big Susitna R.	Vid.	20	0.96	4,1	G	0,1
	4	3	NW	W. of Big Susitna R.	Obs.	21	0.34	4,1	G	0,1
	5	3	NW	W. of Big Susitna R.	Vid.	55	0.51	4,1	G	1,1
	6	3	NW	Little Susitna R.	Obs.	337	0.19	4,1	G	1,1
	7	3	NE	Chickaloon Bay	Vid.	11	1.10	3,2	G	1,1
7/18/95	1	1	NE	Chickaloon Bay	Vid.	29	0.36	4,1	G	0,1
	2	1	NW	McArthur R.	Obs.	1	1.15			
	3	1	NW	Big Susitna R.	Obs.	731	0.36	1,3	G	1,1
7/19/95	1	2	NE	Chickaloon Bay	Vid.	20	0.41	5,4	G	1,1
	2	2	NW	McArthur R.	Obs.	8	0.58			
	3	2	NW	Shirleyville	Obs.	4	0.42			
	4	2	NW	Big Susitna R.	Vid.	348	0.22	4,5	E	1,1
7/20/95	1			Chickaloon Bay	Vid.	16	0.40	1,5	E	1,1
	2+3	3	NW	Big Susitna R.	Vid.	73	0.50	1,5	E	1,1
7/21/95	1	4	NW	Big Susitna R. (E)	Vid.	32	0.65	3,2	G	1,0
	2	4	NW	Big Susitna R. (W)	Obs.	278	0.77	3,2	G	1,0
	3	4	NW	Knik Arm	Obs.	2	0.42			
	4	4	NE	Chickaloon Bay	Obs.	43	0.26	5,3	G	1,1
7/22/95	1	1	S	Big R.	Vid.	17	0.42			
7/24/95	1			Drift R.	Obs.	5	1.05	3,4	F	1,0
	2	4	NW	McArthur R.	Obs.	4	0.68	1,5	P	0,1
	3	4	NW	Big Susitna R. (W)	Vid.	272	0.27	1,5	G	1,1
	4	4	NW	Big Susitna R. (E)	Obs.	94	0.45			
6/11/96	2			Lewis R.	Obs.	13	0.69	1,4	G	1,0
6/12/96	4	1	NE	Pt. Possession	Obs.	48	0.58	5,6	F	1,0
	1			Theodore R.	Obs.	12	0.39	6,4	G	1,1
	2			Lewis R.	Vid.	33	0.60	6,4	G	1,1
	3			Big Susitna R.	Vid.	199	0.19	6,4	F	1,1
6/13/96	1	1	NW	Knik Arm	Obs.	17	0.26	5,4	E	1,1
	2	1	NW	Knik Arm	Obs.	18	0.45	5,4	E	1,1
	3	2	NE	Pt. Possession	Vid.	69	0.26			
	4	1	NW	Ivan R.	Obs.	168	0.20	6,1	G	1,1
	5	1	NW	Big Susitna R.	Vid.	229	0.17			
6/16/96	1	2	NW	Knik Arm	Obs.	37	0.15			
	2	2	NW	Knik Arm	Obs.	28	0.32			
	3	3	NE	Pt. Possession	Vid.	40	0.36	1,4	E	1,1
	4	2	NW	Lewis/Ivan R.	Vid.	365	0.09	6,5	G	1,1
	5	2	NW	Big Susitna R.	Vid.	69	0.23	4,1	E	1,1
	6	2	NW	Big/ Little Susitna R.	Obs.	132	0.39	5,6	E	1,1
	7	2	NW	Little Susitna R.	Vid.	22	0.74			
6/8/97	1	1	NW	Knik Arm	Vid.	30	0.34			
	2	1	NW	Knik Arm	Vid.	63	0.23	5,6	G	1,1
	3	1	NW	Knik Arm	Vid.	76	0.20	1,7	E	1,1
	4	1	NW	Knik Arm	Obs.	2	0.42			
	5+6	1	NW	Knik Arm	Vid.	56	0.17			
	7	1	NW	Knik Arm	Obs.	4	0.42			
	8	1	NE	Chickaloon Bay	Vid.	20	0.32	6,5	G	0,1
	9	1	NE	Chickaloon Bay	Vid.	19	0.43	6,5	G	1,1
	10	1	NW	Big Susitna R.	Vid.	127	0.21	7,1	G	1,1
6/9/97	1	1	S	Tuxedni Bay	Obs.	2	0.42			
	2	2	NW	Big Susitna R.	Obs.	103	0.36	7,5	P	0,1

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Table 1.—Continued.

Date	Group	Survey	Section (Fig. 1)	Sighting location	Estimation method	Group size ($\hat{n}_g$)	CV($\hat{n}_g$)	Obs.[1]	Vis[2]	Seen[3]
6/10/97	1	3	NE	Chickaloon Bay	Vid.	113	0.16	5,1	P	0,1
	2	3	NW	Big Susitna R.	Obs.	140	0.35	6,7	G	1,1
	3	3	NW	Knik Arm	Vid.	153	0.12			
	4	3	NW	Knik Arm	Vid.	60	0.21			
	5	3	NW	Knik Arm	Obs.	2	0.42			
	6	3	NW	Knik Arm	Obs.	9	0.42			
6/10/98	1	1	NW	Fire I.	Obs.	21	0.52			
	2	1	NE	Chickaloon Bay	Vid.	27	0.33	4,7	G	1,1
	3	1	NW	Susitna R.	Vid.	139	0.23	5,8	F	1,0
	4	1	NW	Knik Arm	Obs.	4	0.42			
	5	1	NW	Knik Arm	Obs.	21	0.39			
	6	1	NW	Knik Arm	Obs.	7	0.48			
	7	1	NW	Knik Arm	Obs.	8	0.41	7,4	G	1,1
	8	1	NW	Knik Arm	Obs.	64	0.42	8,5	F	1,1
	9	1	NW	Knik Arm	Obs.	9	0.50			
	10	1	NW	Knik Arm	Obs.	49	0.33			
6/12/98	1	2	NW	Little Susitna R.	Vid.	53	0.28			
	2	2	NW	Knik Arm	Obs.	9	0.89	8,5	G	0,1
	3	2	NW	Knik Arm	Vid.	26	0.46			
	4	2	NW	Knik Arm	Vid.	18	0.53			
	5	2	NW	Knik Arm	Vid.	21	0.37	4,8	G	0,1
	6	2	NW	Knik Arm	Obs.	19	0.66			
	7	2	NW	Knik Arm	Vid.	45	0.51			
	8	2	NE	Chickaloon Bay	Vid.	31	0.40	4,8	F	1,1
	9	2	NE	Chickaloon Bay	Vid.	19	0.68	4,8	F	1,1
6/15/98	1	3	NE	Chickaloon Bay	Vid.	89	0.22	4,8	G	1,1
	2	3	NW	Little Susitna R.	Obs.	2	0.42			
	3	3	NW	Little Susitna R.	Vid.	285	0.14	5,1	E	1,0
	4	3	NW	Knik Arm	Obs.	21	0.42			
	5	3	NW	Knik Arm	Vid.	40	0.21	8,4	G	1,1
	6	3	NW	Knik Arm	Vid.	4	1.08			
	7	3	NW	Knik Arm	Vid.	11	0.66			
6/9/99	1	1	NW	Little Susitna R.	Vid.	314	0.17	5,8	E	1,1
	2	1	NW	Knik Arm	Obs.	54	0.11			
	3	1	NE	Chickaloon Bay	Vid.	29	0.46			
6/11/99	1			Little Susitna R.	Vid.	244	0.41	1,5;8,4	F,P	1,1;1,1
6/12/99	1	2	NE	Chickaloon Bay	Vid.	2	0.44	8,1	E	1,1
	2	2	NE	Chickaloon Bay	Vid.	30	0.19			
	4	2	NW	Beluga R.	Vid.	12	0.52	4,5	E	0,1
	5	2	NW	Big Susitna R.	Vid.	92	0.21	4,5	E	0,1
	6	2	NW	Little Susitna R.	Vid.	178	0.41	1,8	E	1,1
	7	2	NW	Knik Arm	Vid.	38	0.26	5,4	E	1,1
6/13/99	1	3	NW	Big Susitna R.	Vid.	25	0.33	8,4	G	0,1
	2	3	NW	Little Susitna R.	Vid.	258	0.21	8,4	E	1,1
	4	3	NW	Knik Arm	Vid.	17	0.23			
6/7/00	1			Knik Arm	Vid.	44	0.27	1,8	E	1,0
6/8/00	1	1	NW	Little Susitna R.	Vid.	317	0.14	1,4	E	1,1
	2	1	NW	Little Susitna R.	Vid.	33	0.23			
	3	1	NE	Chickaloon Bay	Vid.	11	0.34	4,1	E	1,1
6/11/00	1			Little Susitna R.	Vid.	231	0.12	5,1	E	1,1
	2			Beluga R.	Vid.	2	0.39	4,8	E	1,0
6/12/00	1	2	NE	Chickaloon Bay	Vid.	31	0.18			
	2	2	NE	Chickaloon Bay	Vid.	11	0.23			
	3	2	NW	Little Susitna R.	Vid.	357	0.12	5,4	E	1,1
	4	2	NW	Little Susitna R.	Vid.	27	0.41			
	5	2	NW	Knik Arm	Obs.	13	0.79	5,4	G	1,1
	6	2	NW	Knik Arm	Vid.	3	0.70	5,4	G	1,1
	7	2	NW	Knik Arm	Vid.	49	0.18			
6/13/00	1			Chickaloon Bay	Obs.	9	0.51	1,4	G	1,1
	2			Big Susitna R.	Vid.	156	0.16	1,4	E	1,1
	3			Knik Arm	Obs.	18	0.32	5,8	E	1,1
	4			Knik Arm	Obs.	9	0.68	5,8	E	1,1
	5			Knik Arm	Vid.	28	0.20			

[1] Observer code identifications for the 8 primary Observers; the ordered pairs indicate whether the respective Observers were in the left front or left middle positions; the left rear seat was used by visitors and so is not included here.
[2] Visibility conditions reported by Observers (E, G, F, P) are excellent, good, fair, and poor, respectively.
[3] Sighted (1) or missed (0) groups are indicated in ordered pairs as in the "Obs." column.

stant fraction of the population ($H_y = h N_y$). The likelihood of a particular set of parameter values $L[N_{1994}, (H \text{ or } h), r]$ was estimated as,

$$L\left[N_{1994},(H \text{ or } h)r\right]=\prod_{y=1994}^{1998}\frac{1}{N_y}\, Norm\left[\ln(\hat{N}_y), \begin{Bmatrix} \ln(N_y), y = \\ 1994,\ 1996-1998 \\ \ln(N_y - H) \text{ or } \\ \ln\left(N_y(1-h)\right), y = 1995 \end{Bmatrix}, \ln\left(1+CV^2(\hat{N}_y)\right)^{\frac{1}{2}}\right],$$

where $Norm(x, \mu, \sigma)$ is the probability density at x from the normal distribution with mean μ and standard deviation σ. The harvest model with the larger likelihood at the best parameter fit was then chosen as the more likely. A set of 10,000 simulations of the chosen model were run using parameter values drawn from prior distributions, following a Monte Carlo integration approach (Press, 1989) to approximate prior and posterior distributions on depletion level (D_y). This was defined as:

$$D_y = \frac{N_y}{N_{1994}}$$

using the selected harvest model.

The model requires three parameters (N_{1994}, either H or h, and r) and distributions for those parameters. The initial population size, N_{1994}, was drawn from the lognormal distribution used to estimate the confidence interval for the abundance estimate. The harvest, H, was drawn from a uniform distribution between 50 and 150 whales, and the harvest rate, h, was drawn from a uniform distribution between 5% and 40% of the population per year. The per capita growth rate, r, was chosen from a uniform distribution of –10% to +10% per capita increase. Negative growth rate was included in the prior distribution to allow for the possibility that habitat factors other than hunting were driving the population down. The results from the simulation runs were grouped into 10% bins by D_y. To create a probability distribution for D_y, the likelihoods were averaged in each bin, and the averages were scaled so that the sum of the averages over all bins equaled 1.

Results

There was a total of 144 sightings of groups of belugas made during aerial surveys of Cook Inlet in 1994–2000. Of these, 112 were used to estimate abundance for the respective years (Table 1). Many of these are resightings of groups encountered on different survey days and years. Of the 112 groups, abundances for 65 were estimated from video and 47 from observer counts (Table 1). Hobbs et al. (2000) provide abundance estimates for each of these sightings, including corrections for availability and detection biases.

A total of 81 whale groups (Table 1) were reported while pairs of observers were searching independently (the search effort was not considered independent if there was open verbal communication, e.g. during weather checks or additional sightings made while a group was being circled). Logistic regression indicated the best model fit using the following covariates: 1) the natural logarithm of group size, 2) observers clumped into three sighting-performance categories, and 3) visibility recoded as a numeric variable (Table 2). The correction for whales in missed groups was 1.015 (CV = 3%) for the years 1994–98 and 1.021 (CV = 1%) for the years 1999 and 2000.

Abundances were calculated for each geographical section within Cook Inlet (Fig.1) and totaled for each year 1994–2000 (Table 3, Fig. 2). Calculated abundances were 653 (CV = 0.43) in 1994, 491 (CV = 0.44) in 1995, 594 (CV = 0.28) in 1996, 440 (CV = 0.14) in 1997, 347 (CV = 0.29) in 1998, 367 (CV = 0.14) in 1999, 435 (CV = 0.23, 95% CI = 279–679) in 2000. For management purposes the current N_{best} = 435 and N_{min} = 360 (Wade and Angliss, 1997).

Of the two models considered for the Bayesian analysis, the best fit occurred in the model with a constant annual harvest (likelihood = 1.70 E-13, H = 135, N_{1994} = 706 and r = 0.10, D_{1998} = 0.49, D_{1999} = 0.32). The best fit for the model with a proportional harvest was slightly less likely (likelihood = 1.54 E-13, h = 0.22, N_{1994} = 748 and r = 0.07, D_{1998} = 0.49, D_{1999} = 0.41). Applying the Bayesian analysis to the constant harvest model indicates that—although the most likely depletion level at the time of the survey in 1998 was below 50%—the probability that the population was depleted at that time (i.e. probability that $N_{1998}/N_{1994} = D_{1998} < 50\%$) was 0.47 (Table 4, Fig. 3). Projecting the model forward 1 year to June 1999 shows the most likely depletion level was between 0.3 and 0.4, and the probability that $D_{1999} < 50\%$ was 0.72 (Table 4). Note that this analysis only considers depletion during the period 1994–98. If the population was significantly less than carrying capacity in 1994 when these abundance estimates began, then

Table 2.—Coefficients of the logistic regression to estimate the probability that a group of belugas was seen by an observer while doing aerial surveys in Cook Inlet. Observers were clumped into three groups based on performance: A, B, or C. Group A was the index group. Each visibility was given a numeric value (Excellent = 0, Good = 1, Fair = 2, Poor = 3) and treated as a linear variable rather than a categorical variable. The best model was chosen by comparing the AIC.

Coefficients	Value	SE	t value
1994–1998			
Intercept	2.37	1.24	1.91
Ln(group size)	0.34	0.21	1.65
Observer group B	–1.26	0.78	–1.63
Observer group C	–2.02	0.80	–2.54
Visibility Number	–1.03	0.37	–2.77
1999–2000			
Intercept	–0.56	0.72	–0.78
Ln(group size)	0.53	0.21	2.49

Table 3.—Estimated abundance of belugas by year and section in Cook Inlet.

Year	Northwest	CV	Northeast	CV	South	CV	Total	CV
1994	580	47%	48	108%	25	19%	653	43%
1995	444	48%	31	43%	17	43%	491	44%
1996	542	30%	52	37%	0		594	28%
1997	362	9%	76	69%	2	43%	440	14%
1998	292	32%	55	60%	0		347	29%
1999	336	15%	31	25%	0		367	14%
2000	408	23%	27	82%	0		435	23%

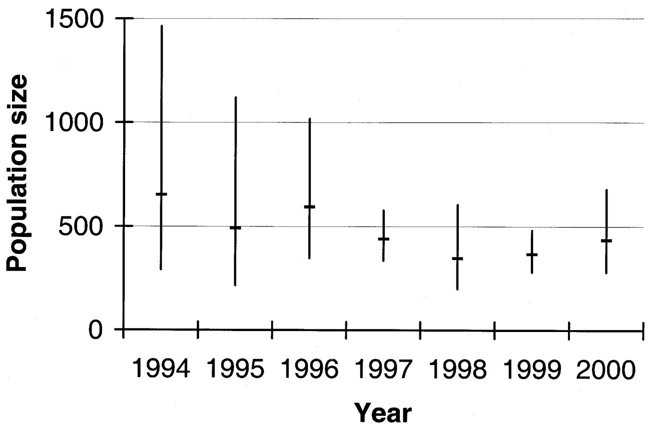

Figure 2.—Estimated abundance of Cook Inlet belugas for the years 1994 through 2000. Marks indicate point estimates, and vertical bars indicate the 95% log-normal confidence intervals.

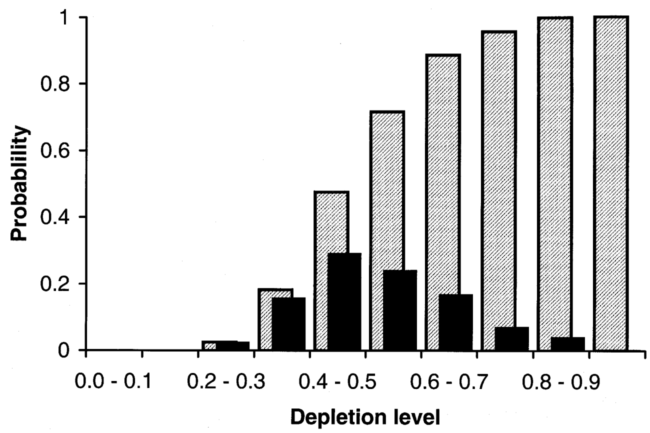

Figure 3.—Probability distribution of depletion level of the 1998 abundance below the 1994 population size (N_{1998}/N_{1994}). Dark columns are the probability that the depletion level falls into the indicated range. Light columns are the cumulative distribution and indicate the probability that the depletion level is in the indicated range or lower.

the depletion would be greater. The Native take of belugas in Cook Inlet ceased in 1999 (Mahoney and Shelden, 2000), and there has been no evident decline in abundance since that time (Fig. 2); however, there are too few years since then to reliably quantify a new trend in abundance.

Table 4.—Probability distribution from Monte Carlo simulations of depletion level at the time of the June 1998 survey counts and projected to the June 1999 survey assuming that hunting continued at the same level.

Depletion level	1998 probability	Cumulative probability	1999 probability	Cumulative probability
0.0 to 0.1	0.000	0.000	0.001	0.001
0.1 to 0.2	0.000	0.000	0.080	0.081
0.2 to 0.3	0.025	0.025	0.199	0.280
0.3 to 0.4	0.158	0.183	0.256	0.535
0.4 to 0.5	0.292	0.475	0.189	0.725
0.5 to 0.6	0.241	0.716	0.141	0.866
0.6 to 0.7	0.169	0.885	0.076	0.942
0.7 to 0.8	0.071	0.955	0.039	0.980
0.8 to 0.9	0.041	0.997	0.018	0.998
0.9 to 1.0	0.003	1.000	0.002	1.000

Discussion

The rigor and intensity of the protocol applied in the surveys reported here make the surveys highly comparable among years (1994–2000) but not necessarily comparable to surveys conducted by other researchers prior to the 1990's (reviewed in Rugh et al., 2000). Although earlier surveys in Cook Inlet often resulted in beluga counts of about 300–400, these surveys used different protocols and may not have even been focused on belugas. Therefore, it is inappropriate to attempt abundance trend analyses based on counts from 10- to 30-yr-old studies with very little supporting documentation.

The abundance estimates presented here are very sensitive to statistics on the typical surfacing interval of a beluga. The surfacing interval information was based on data from 5 belugas in Cook Inlet, each tagged separately and tracked for only a few hours (Lerczak et al., 2000). Individuals showed a wide range of dive intervals, and very little information is available on the degree of correlation in dive behavior within large groups. If all whales in a group dove in complete synchrony, or if each of the whales in a group dove at truly random intervals, estimates of the number of sub-surface whales would be relatively straightforward. But the reality is that dive behavior may be correlated between individuals engaged in the same activities, and it may be correlated over extended periods for the same individual. This correlation contributes to the wide ranges in counts from one aerial pass to the next even when other variables (observer, visibility, etc.) have not changed. Clearly what is needed to decrease the variance on this important parameter is a larger sample size of tagged whales and a better understanding of the relationship between dive intervals and behaviors that can be identified from the air.

A significant portion of the variability in the annual abundance estimates is the result of variation among survey days. This variation is greater than can be explained by the variances for those days. Thus, we must conclude that there remain some sources of variability that have not been accounted for. The most likely candidate is variability resulting from the correlated dive behavior discussed above. We assumed that each whale was choosing dive intervals at random from its own dive interval distribution, when in fact these choices may be correlated among individuals in a group. If this is the case, then the variances of the group size estimates and the daily abundance estimates may have been underestimated.

The high density of beluga aggregations has made them easy to find and convenient to work with in the video recordings. This density also made them difficult to count while passing by them in an aircraft. This difficulty might result in an underestimation of a trend in abundance if observers tend to undercount more at high densities than at low densities; as group sizes decline from year to year, undercounting would diminish, and observers' counts would become more accurate. Hobbs et al. (2000) provide exacting corrections to account for this form of detection bias in observer counts, such that this concern is minimized in the final abundance estimates.

Although our field methods and analyses were designed to satisfy the three criteria listed in our introduction, several field seasons were required to accumulate the necessary data and auxilliary experimental results to utilize the methods described above and in Hobbs et al. (2000). To accomodate the need for a timely preliminary abundance estimate, an ad hoc approach was developed from the 1994 survey data, resulting in an estimate of 749 whales (Hobbs et al.[1]). This preliminary estimate for 1994 has been replaced by the more accurate estimate of 653 whales. Also, a preliminary estimate of 357 whales from the 1999 survey data is replaced here by the final estimate of 367.

In 1999 a digital camera system was introduced to collect the counting video recordings (Hobbs et al., 2000). The experiments necessary to develop a correction for whales at the surface that were missed by the video did not have sufficient sample sizes until the completion of the 2000 survey. Thus a preliminary abundance estimate was developed using video only for groups where it was certain that no whales were missed and relying on observer counts for the remainder of the group size estimates. With the completion of the necessary video experiments in 2000, these group size estimates were revised, and the abundance estimate was recalculated.

Apparently, only a few whales (1.5%) were in groups missed during these aerial surveys of Cook Inlet, based on results from the paired-observer effort. Single observers would have missed more whales (about 12%). This paired, independent observer technique suffers one underlying assumption: that we are able to account for the factors resulting in heterogeneity within the sampling. In these surveys, both of the paired observers had equal sighting opportunities. Evident heterogeneity resulted from group size, observer performance, and visibility conditions; the most important factor was group size.

When approaching single whales or small groups, sighting opportunities were limited to very few surfacings and changed significantly with time, but large groups provided nearly continuous sighting cues at a fairly constant rate. Observer performance was roughly correlated with experience such that inexperienced observers were more likely to miss groups, but after the experience of a few survey days, each observer's sighting rate approached an individual average. The impact of declining visibility conditions is evident (DeMaster et al., 2001) and supports the survey design decision to avoid surveying or excluding results when visibility was reduced.

One other source of potential heterogeneity is the distance of groups from the trackline. We did not use distance as a covariate in this analysis and consequently have assumed that detection does not decline significantly with distance. Because the trackline during coastal surveys was only 1.4 km offshore and virtually all beluga groups occurred between the trackline and shore, very few whale groups would have been missed as a function of distance alone.

Although river mouths or narrow inlets temporarily widened the effective search area, the survey also included flights up most rivers and through bays as far as was reasonable. Other than these minor irregularities, the search area was fairly constantly 1.4 km wide, and because whales were sometimes visible out to 6 km (Rugh et al., 2000), there is no evidence that distance across the transect sector was a critical factor in missing whale groups.

There have been many attempts to find appropriate correction factors for whales missed during aerial counts of belugas. Estimates have ranged from 1.15 to 2.75 (reviewed in Hobbs et al. 2000), but they do not necessarily account for all critical factors, and most are not applicable to the situation in Cook Inlet where the water is nearly opaque. The precision and multiple repetitions used in the current survey design in Cook Inlet, along with the video analysis and time-at-surface ratios recorded within the inlet, have allowed this study to produce abundance estimates with relatively high accuracy.

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