

A NEW ABUNDANCE ESTIMATE FOR VAQUITAS: FIRST STEP FOR RECOVERY¹

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ABSTRACT

A line-transect survey specifically designed to estimate vaquita (*Phocoena sinus*) abundance over its entire range was carried out by three boats in the summer of 1997. There was a total of 125 sightings of vaquita groups, mainly due to the use of large 25×150 binoculars, which were seven times more effective in detecting vaquitas than hand-held 7× binoculars. Results confirmed that the range of the vaquita is restricted to the northwestern corner of the Gulf of California, Mexico, but that the boundaries of the Upper Gulf of California and Colorado River Delta Biosphere Reserve do not correspond well with the distribution of vaquitas. The shallow water north of the town of San Felipe was found to have a higher density of animals than had been indicated by previous surveys. The total population size was estimated to be 567 animals, with a 95% confidence interval from 177 to 1,073. This estimate is an improvement over previous estimates, which had low numbers of sightings, relied on parameters taken from other species, and/or did not cover all areas where vaquitas could potentially be found. The 1997 estimate was more than twice the 1993 estimate, but there are several reasons why the numbers cannot be directly compared, and it should not be concluded the population is increasing. This first complete estimate of vaquita abundance can be a beginning for the recovery of this highly endangered species.

¹ An important legacy from Ken Norris, not only to marine mammalogists but to all interested in preserving our natural world, was to be conscious of how fragile our natural surroundings can be. Unfortunately the vaquita is in danger of extinction. It would be a shame if this species, first described by Norris, were also the first cetacean in modern times to go extinct. We hope that current efforts by Mexico and the International Committee for the Recovery of the Vaquita will bear fruit. It is our honor to dedicate this paper, which we hope will mark the first step away from extinction, to the memory of Ken Norris.

Key words: vaquita, *Phocoena sinus*, abundance, line-transect, Gulf of California, endangered species.

The vaquita, *Phocoena sinus*, was described scientifically in 1958 based on skeletal material (Norris and McFarland 1958). Because of its inconspicuous behavior, small size, and turbid habitat, the vaquita remained elusive, and for many years after its description there was no clear information on its population size, range, or even external appearance. Informed but non-statistical "guesstimates" of population size ranged from 50 to 1,000 animals (Barlow *et al.* 1993, Vidal 1995). The first statistically designed survey with enough sightings for a solid estimate of abundance took place in 1993 as part of a larger multi-species cruise. Those data produced an estimate of 224 vaquitas, with a 95% confidence interval from 106 to 470 (Barlow *et al.* 1997). However, because the cruise was not specifically designed for vaquitas, the 1993 survey did not cover all potential vaquita habitat. Furthermore, to estimate abundance it was necessary to use one parameter [$g(0)$] taken from studies of harbor porpoises (*Phocoena phocoena*).

Even before the small size of the vaquita population became clear, concern for its conservation status had been expressed for a number of years, both within Mexico and internationally, due to its limited range (Brownell 1986, Gerrodette *et al.* 1995) and mortality in fishing nets (Vidal 1995, D'Agrosa *et al.* 1995, D'Agrosa *et al.*, in press). The vaquita is classified in the most severe category ("critically endangered") by the World Conservation Union (IUCN 1996), and by the Convention on International Trade in the Endangered Species of Wild Fauna and Flora (CITES 1998). The Mexican government has also listed vaquitas as endangered (DOF 1994). The World Conservation Union has concluded that the extinction of the vaquita is likely unless conservation efforts are substantially increased (IUCN 1996).

In 1993 the Mexican government established the Upper Gulf of California and Colorado River Delta Biosphere Reserve, which was intended to protect the vaquita, among other species. In 1996 the Mexican government further announced a recovery strategy for *Phocoena sinus* (Anon. 1996) and formed the International Committee for the Recovery of the Vaquita. At its first meeting, the committee recommended that a new estimate of abundance was needed as a first step in a plan for the recovery of the species. As a result, the National Fisheries Institute of Mexico and the National Marine Fisheries Service of the U.S. carried out a joint cruise in 1997 with the specific objective of producing a new and comprehensive estimate of abundance for this rare cetacean. The results of that cruise are reported here.

In recent years much additional information has been published about vaquitas, including studies of genetics (Rosel and Rojas-Bracho 1999, Taylor), habitat (Silber 1990, 1999), diet (Pérez-Cortés 1996), behavior (Silber *et al.* 1988), morphology (Brownell *et al.* 1987, Torre-Cosio 1995), life history (Hohn *et al.* 1996), mortality in fishing nets (D'Agrosa *et al.* 1995; D'Agrosa *et al.*, in press), and conservation status (Vidal 1995, Rojas-Bracho and Taylor 1999).

METHODS

Study Area and Density Estimation

The range of the vaquita is confined to the northwestern corner of the Gulf of California, Mexico, near the mouth of the Colorado River (Brownell 1986, Silber 1990, Gerrodette *et al.* 1995). The area covered in this study included all previously confirmed vaquita sightings and records, both published and unpublished. Based on density of animals and water depth, the study area was stratified into four areas: core, southeast, shallow and delta (Fig. 1). The core and southeast areas (20–100 m deep) were surveyed by the 52-m R/V *David Starr Jordan* (DSJ), the shallow area (5–20 m deep) by the 21-m R/V *BIP XI* (BIP), and the delta area (<5 m deep) by a 10-m skiff (panga) with a specially constructed aluminum viewing platform. The shallowest margins of two bays in the eastern part of the study area (Adair and San Jorge Bays) were inaccessible to the BIP (Fig. 1). Transect lines were laid out as grids with a random starting point in the core and southeast areas, as zig-zag lines across depth contours in the shallow area, and as simple navigation in the river channel in the case of the panga in the delta area.

Field work took place in the summer of 1997. On each vessel a visual search was carried out by a rotating team of three observers as the ship moved along the trackline at a speed of 11 km/hr. On the DSJ, three pairs of large 25×150 binoculars were mounted on the flying bridge at an eye height of 10.7 m. A fourth person recorded data on a laptop computer. On the flying bridge of the BIP (eye height 6.3 m) and on the viewing platform of the panga (eye height 3 m), two observers searched with 7×50 binoculars, while a third searched mainly by eye and occasionally with 7× binoculars. This observer also entered data into a computer. Each ship recorded oceanographic data and weather conditions. Geographic positions using the Global Positioning System were automatically recorded *via* the serial port of the computer.

Vaquita abundance was estimated using distance sampling (Buckland *et al.* 1993). Perpendicular distance to a sighted group was calculated by trigonometry, given angle and radial distance. Angle of the group in relation to the ship's course was measured by azimuth rings on the pedestal-mounted 25× binoculars, or by angle boards for the hand-held 7× binoculars. Radial distance was estimated using reticle lines in the binoculars. Reticle values were converted to angular values, and angular values were converted to distance with the formulas:

$$A = 1 + \tan(\text{ang}_1 - \text{ret} * \text{angret})$$

$$B = 2 * (er + b) * \tan(\text{ang}_1 - (\text{ret} * (\text{angret})))$$

$$C = (er + b)^2 - er^2$$

$$X = \frac{-B - \sqrt{B^2 - 4AC}}{2A}$$

$$RD = \arcsin\left(\frac{X}{er}\right)er \quad (1)$$

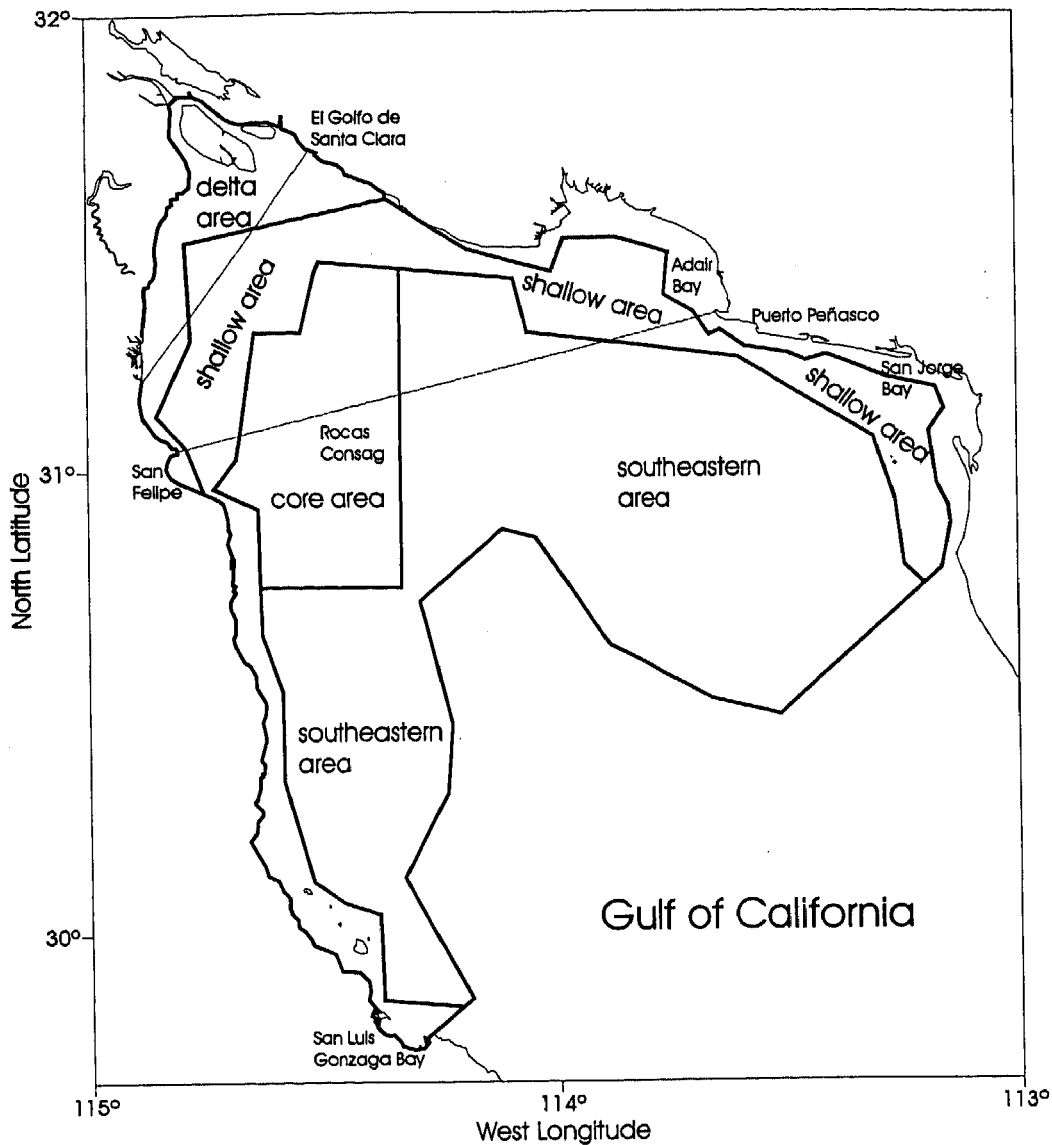


Figure 1. Study area in northern Gulf of California for 1997 vaquita cruise, showing strata discussed in text. Lighter straight lines show boundaries with Upper Gulf of California and Colorado River Delta Biosphere Reserve. Line between San Felipe and Puerto Peñasco is southern boundary of buffer zone, and line running southwest from El Golfo de Santa Clara is southern boundary of nuclear zone of reserve.

where ang_1 is the angle of inclination of the binoculars when positioned with reticle 0 in horizon; ret is the number of reticle lines to the group sighted; $angret$ is the angular value between adjacent reticle lines; er is the earth radius; b is eye height above the water; A , B , and C are the parameters to solve a second degree equation; X is the least root of the solution; and RD is the curvilinear radial distance to the observed group. Our algorithm gave the same results as the algorithm of Lerczak and Hobbs (1998).

Density of animals D was estimated by the standard line-transect estimator

$$D = \frac{nE(s)f(0)}{2Lg(0)} \quad (2)$$

where n was the number of sightings, L the total distance searched, $E(s)$ the expected group size, $f(0)$ the probability density function of distance and $g(0)$ the detection probability function, both evaluated at zero distance. Total density was estimated by averaging the density estimates from each stratum, weighting by area. Abundance was estimated by multiplying the estimated density by the size of the study area.

Variances were estimated by two methods. Analytical variances were estimated for each parameter except $g(0)$ using the *delta* method (Seber 1982), and the variance of total abundance was estimated using weighted averages of the variances of encounter rate, school size, $f(0)$ and $g(0)$. Variances were also estimated using a bootstrap procedure. A Visual Basic 5.0 program was written to generate 2,000 replicate samples, using the D35 engine routine in Distance (see below) to estimate $f(0)$. Each replicate sample contained the same total distance effort as the original sample in each stratum, obtained by sampling transects with replacement and trimming effort and sightings from the last transect selected. At each bootstrap iteration, total abundance was estimated. The estimations for the core area included the selection of the best model and size-bias regression at each replicate. The resulting variances thus included the uncertainty from model selection and average group size calculation. The 95% confidence interval for each parameter was obtained from the quantiles of the bootstrap replicates. The quantiles were modified by the BC_a method (bias-corrected and accelerated confidence interval: Efron and Tibshirani 1993). Because the bootstrap variances include most of the uncertainty in the estimates, only these variances are reported. The analytical variances served as reference points against which to check the bootstrap procedure.

Core and Southeast Areas

Estimation of $f(0)$, $E(s)$, and the encounter rate n/L was carried out using Distance 3.5 Release 4 (Thomas 1999). Uniform, half-normal, and hazard-rate models, with and without cosine, polynomial, and Hermite-polynomial functions were used for modeling the detection function; the model with the lowest Akaike Information Criterion (AIC) was selected as the best model. Expected group size was estimated using the bias-correction procedure within Distance at a type 1 error level of $\alpha = 0.15$, as recommended by Buckland *et al.* (1993). Transects (sampling units) were uninterrupted periods of searching effort, typically about one hour long.

Distance sampling assumes that the animals do not respond to the ship before they are detected. The effects of responsive movement were investigated by an analysis of re-sightings, that is, the observation of the same group on more than one occasion. We estimated the distance at which vaquitas tended to move away from the ship. The change in radial distance between the group and the vessel on successive sightings was regressed on radial distance. The

distance at which the change was zero, estimated by regression, was taken as the minimum distance at which vaquitas do not react strongly to the ship. To account for heteroscedasticity, we used a regression weighted by the inverse of variance, which was assumed proportional to the square of the independent variable (radial distance), and the quasi-Newton algorithm to minimize the weighted least-squares function. Swimming speed was measured by distance between positions on successive sightings divided by time. The effects of sea state (Beaufort) on the detection process were investigated with a χ^2 analysis of sighting rates.

Because vaquitas travel in small groups and surface inconspicuously, they are difficult to detect, and it was important to estimate the probability that animals directly on the trackline are detected [$g(0)$]. On the DSJ this quantity was estimated by comparing sightings made by two independent observer teams. The team on the flying bridge used $25\times$ binoculars as described previously; the team on the bridge (eye height 8.3 m) used $7\times$ binoculars. Observers on each platform could communicate with the data recorder, but not with observers on the other platform. The data recorder determined when a sighting was detected by both teams, aided by maps of sightings in real time on the computer. Histograms of sighting frequencies and a preliminary fit of the few bridge sightings indicated that the probability of detection was approximately constant in the first 500 m for both platforms, simplifying the problem to a Petersen mark-recapture approach (Buckland *et al.* 1993, p. 210). Given the number of groups detected by each platform (n_{bridge} and n_{flying}) and the number of groups detected by both (n_{recap}), $g(0)$ was estimated for each platform as

$$g(0)_{flying} = \frac{n_{recap}}{n_{bridge}} \quad \text{and} \quad g(0)_{bridge} = \frac{n_{recap}}{n_{flying}}.$$

Variance of $g(0)$ was estimated by 1,000 bootstrap replications, using the sightings as sampling units.

Shallow Area

Sightings and effort by the *BIP* in the shallow area were used to estimate encounter rate n/L and mean school size $E(s)$, but there were too few sightings to model the detection function. In anticipation of the small number of sightings and the absence of an independent team to estimate $g(0)$, the survey design called for the *BIP* to conduct transects in the core area in order to compare sighting efficiency with the *DSJ*. The ratio $f(0)/g(0)$ for the *BIP* was estimated by rearranging Eq. 2:

$$\left(\frac{f(0)}{g(0)} \right)_{BIP} = \frac{2L_{BIP}D_{DSJ}}{n_{BIP}E(s)_{DSJ}}. \quad (3)$$

As indicated, this estimation used density D and school size $E(s)$ estimated from the *DSJ*'s data in the core area, and sightings n and effort L from the

BIP's data in the core area. On the assumption that the detection process for the *BIP* in the shallow area was the same as in the core area, this ratio was used with the *BIP*'s sightings and effort in the shallow area to estimate density.

RESULTS

Core and Southeast Areas

The *David Starr Jordan* carried out 1,609 km of search effort from 16 to 31 August (first leg) and 6 to 19 September (second leg). There were 113 sightings of vaquita groups in the core area and none in the southeast area (Fig. 2). The sighting rate was not the same under different Beaufort conditions ($\chi^2 = 109.1$, d.f. = 6, $P < 0.0001$). Between Beaufort 0 and 2 more groups were observed than expected, while the opposite happened at higher values. To ensure a more homogeneous sample, only effort and sightings in Beaufort 0–2 were used for the estimate of abundance.

Movement of vaquitas was significantly related to distance from the ship ($r = 0.64$; $F[1,78] = 52.86$; $P < 0.00001$). Groups closer to the ship moved away, while groups farther from the ship allowed the ship to move closer to them (Fig. 3). The radial distance at which there was no change in distance on successive sightings, as calculated from the regression, was 913 m, so this was considered the minimum radial distance at which no reaction to the ship occurred (Fig. 3). This assertion was further tested by analyzing differences in swimming speed of vaquitas in the intervals ≤ 913 m and > 913 m. The average speed at radial distances ≤ 913 m was significantly higher (11.3 km/h) than at greater distances (8.2 km/h) ($t = 2.14$, $df = 14$, $P = 0.04$). Therefore, to meet the assumption that animals did not react to the vessel before sighting, only groups detected at a radial distances > 913 m were included in the analysis.

The data set used to estimate $g(0)$ included sightings made at radial distances > 913 m and perpendicular distances < 500 m. This set was composed of 27 sightings by the flying bridge team, 7 by the bridge team, and 4 groups detected by both. This gave an estimate for $g(0)$ of 0.571 (CV = 0.33) for observers on the flying bridge using 25 \times binoculars (Table 1) and 0.148 for observers on the bridge using 7 \times binoculars.

For estimating abundance, the data set for the core area included 70 sightings on 32 transects that totaled 439.8 km, giving an encounter rate of 0.159 sightings/km (Table 1, Fig. 2). The total area of the core stratum was 2,659.7 km². The model with the lowest AIC was a uniform function with cosine series expansion of order 1 (Fig. 4). A χ^2 goodness-of-fit test found no evidence to reject the model ($P = 0.922$). The same procedure applied to truncated data (10%) gave a similar curve but with a lower P value ($P = 0.870$). Based on this test and an inspection of the histograms, the untruncated data were used to estimate $f(0)$ as 0.552 km⁻¹, or an effective strip half-width of 1.81

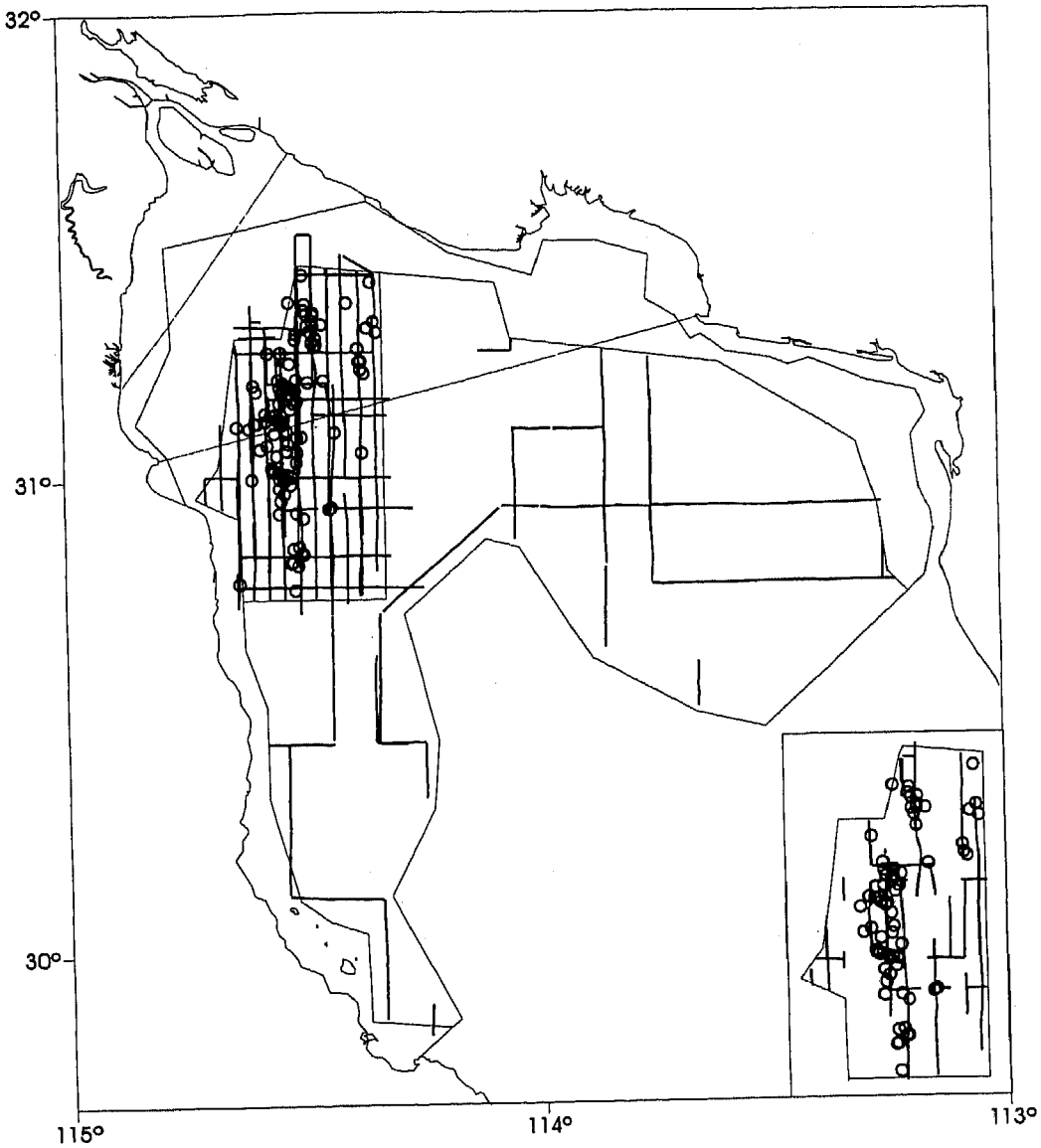


Figure 2. Total survey effort (thin lines) and sightings (circles) aboard *David Starr Jordan*. Inset map in lower right represents effort and sightings used to estimate abundance in core area.

km (Table 1). The size-bias regression was not significant, so the observed mean school size of 2.0 was taken as the expected value.

These estimates combined to give an estimated density of 0.154 vaquitas/km² or 409 vaquitas (CV = 0.61) in the core area (Table 1). Most (54%) of the variance in the estimate was due to variance from $g(0)$, because of the small number of sightings used to estimate this parameter, particularly from bridge deck platform. The encounter rate was another important component of variance (39%), reflecting the extremely clumped distribution of vaquita groups in the core area.

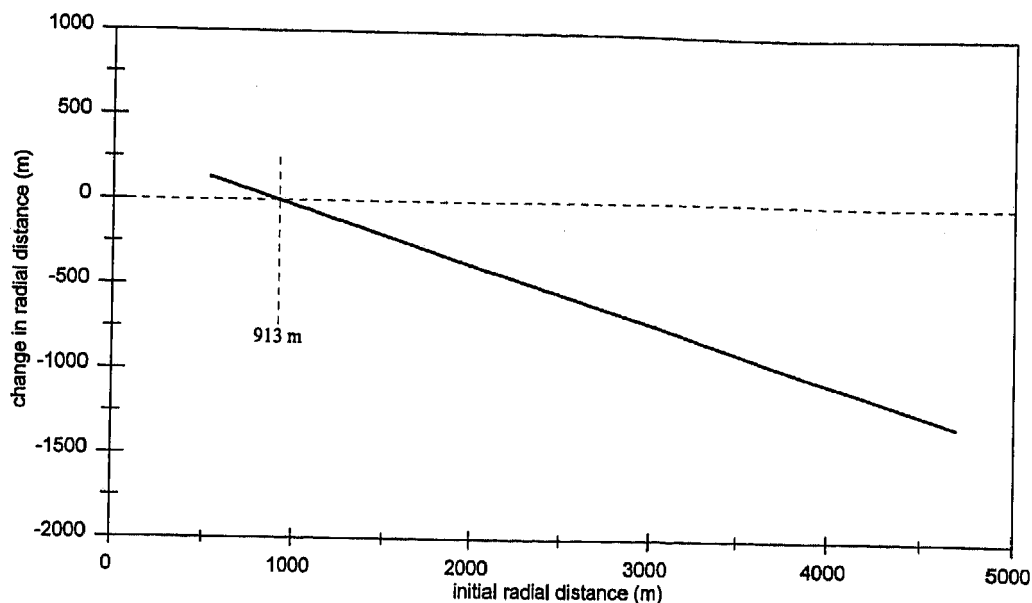


Figure 3. Movement of vaquitas in response to *David Starr Jordan*. Graph plots change in distance from ship on successive sighting as a function of initial radial distance. Positive values on y-axis mean movement away from ship. Weighted least-squares regression line indicates that vaquitas tended to move away when ship was within 913 m.

Shallow and Colorado River Delta Areas

The *BIP XI* surveyed 1,065 km in the shallow area and 579 km in the core area between 17–31 August (first leg) and 7–23 September (second leg) with a total of 12 sightings of vaquita groups (Fig. 5). The panga surveyed 111 km in the Colorado River Delta area on 18, 19, and 21 September and had no sightings.

Of the *BIP*'s 12 sightings, 7 were under Beaufort conditions lower than 3, but only one of those was in the core area. The remaining 5 sightings were in the core area in Beaufort 3 conditions. In order to obtain a larger sample for stable estimation of the ratio $f(0)/g(0)$, sightings and effort in the core area in Beaufort 0–3 for both the *BIP* and *DSJ* were used to estimate the parameters in Eq. 3. Under these conditions, $E(s)_{DSJ} = 1.98$ vaquitas/sighting, $D_{DSJ} = 0.105$ vaquitas/km², $n_{BIP} = 6$ sightings, and $L_{BIP} = 381.0$ km, giving an estimate of 6.78 (CV = 0.80) for the ratio $f(0)/g(0)$ for the *BIP* (Table 1).

For estimating abundance in the shallow area, data were post-stratified into a sub-area adjacent to the core area where all vaquita sightings occurred (Fig. 5). Density and abundance were estimated only for this portion (1,327 km²). In this sub-area, 6 sightings with a mean group size of 2.0 vaquitas occurred during 342 km of search effort in 25 transects. The estimated density of vaquitas was 0.119 vaquitas/km², or 158 vaquitas (CV=0.94) in the sub-area (Table 1). Estimated density and abundance in the rest of the shallow area and in the Colorado River Delta area was zero. Almost all variance in the abundance estimate (94%) was due to variance in the ratio $f(0)/g(0)$, because of the

Table 1. Point estimates and bootstrap estimates of variability of the parameters used to estimate vaquita density and abundance. The bootstrap coefficient of variation (CV) was calculated as the bootstrap SE/Mean, and the 95% confidence interval (CI) was estimated by the quantiles of the bootstrap distribution (BC_a method). $f(0)$ = probability density at the trackline in km⁻¹, n/L = encounter rate in schools/km, DS = density of schools/km², $E(g)$ = expected school size, $g(0)$ = probability of detection at the trackline, D = density of animals/km², N = abundance.

Parameter	Bootstrap estimates				
	Point estimate	Average	S.E.	Percent C.V.	95% C.I.
<i>Core Area, DSJ, Beaufort 0-2</i>					
$f(0)$	0.552	0.583	0.097	16.58	0.469
n/L	0.159	0.162	0.056	34.73	0.073
DS	0.077	0.104	0.064	61.37	0.023
$E(g)$	2.000	2.006	0.126	6.27	1.688
$g(0)$	0.571	0.506	0.166	32.71	0.286
D	0.154	0.208	0.127	61.13	0.040
N	409	552	338	61.13	105
<i>Core Area, DSJ, Beaufort 0-3</i>					
$f(0)$	0.571	0.632	0.118	18.63	0.490
n/L	0.107	0.108	0.034	31.59	0.051
$E(g)$	1.975	1.946	0.098	5.04	1.806
D	0.105	0.145	0.084	58.29	0.034
<i>Core Area, BIP, Beaufort 0-3</i>					
n/L	0.016	0.018	0.006	35.23	0.003
$f(0)/g(0)$	6.777	9.845	7.902	80.27	2.134
<i>Shallow Area, BIP, Beaufort 0-3</i>					
n/L	0.018	0.018	0.007	42.15	0.003
DS	0.059	0.085	0.079	92.71	0.008
$E(g)$	2.000	2.004	0.327	16.31	1.000
D	0.119	0.170	0.159	93.80	0.015
N	158	225	211	93.80	20
<i>Combined estimates</i>					
D	0.142	0.195	0.099	50.72	0.044
N	567	778	394	50.72	177
					1073

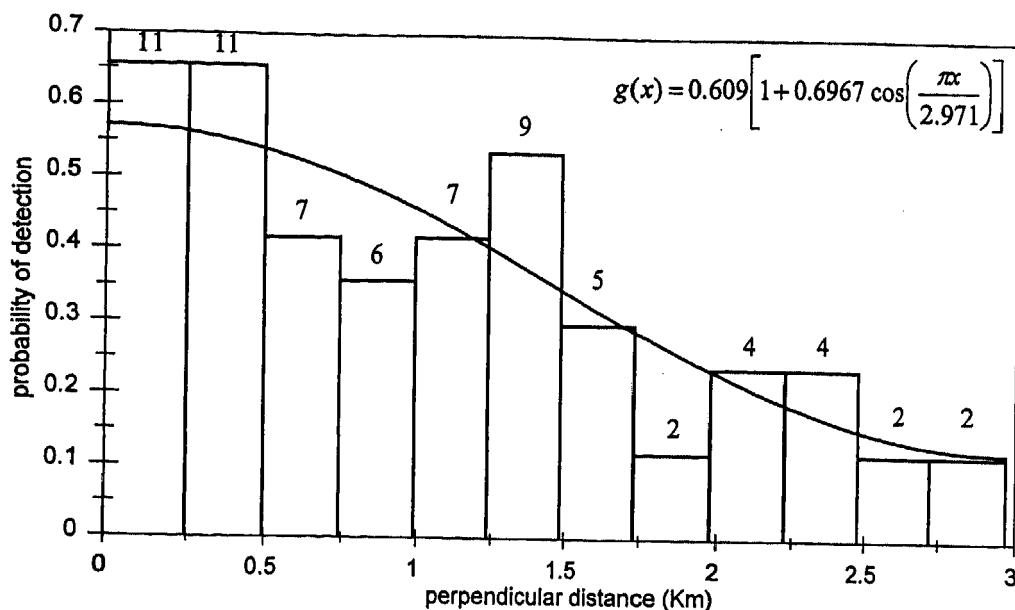


Figure 4. Frequency histogram and cosine detection function for *David Starr Jordan* in core area in Beaufort conditions 0-2. Numbers over histogram bars show number of sightings.

small number of sightings by the *BIP* in the core area available to estimate this quantity.

Combined Estimate and Bootstrap Variance

The estimates from the core and shallow sub-area were combined to obtain the overall abundance. The pooled point estimate of density was 0.142 vaquitas/km², and the total point estimate of abundance was 567 vaquitas (Table 1). The analytical SE of the total abundance estimate using the *delta* method (Seber 1982) was 266 vaquitas, the analytical CV was 0.47, and the 95% log-normal confidence interval was from 237 to 1,358 vaquitas.

The bootstrap estimates of variance for the combined estimates of density and abundance were larger than the analytical estimates by the *delta* method. This was primarily because the bootstrap estimates included additional variability due to (a) model selection for $f(0)$ estimation and (b) size-bias correction of average group size. Therefore the bootstrap estimation represented the variability better, and the bootstrap values are reported in Table 1. The bootstrap CV for overall abundance was 0.51, and the 95% BC_a quantile confidence interval on the total estimate was from 177 to 1,073 vaquitas (Table 1).

DISCUSSION

Population Size

An estimate of population size is a fundamental quantity necessary for effective conservation and management of endangered species. The transect sur-

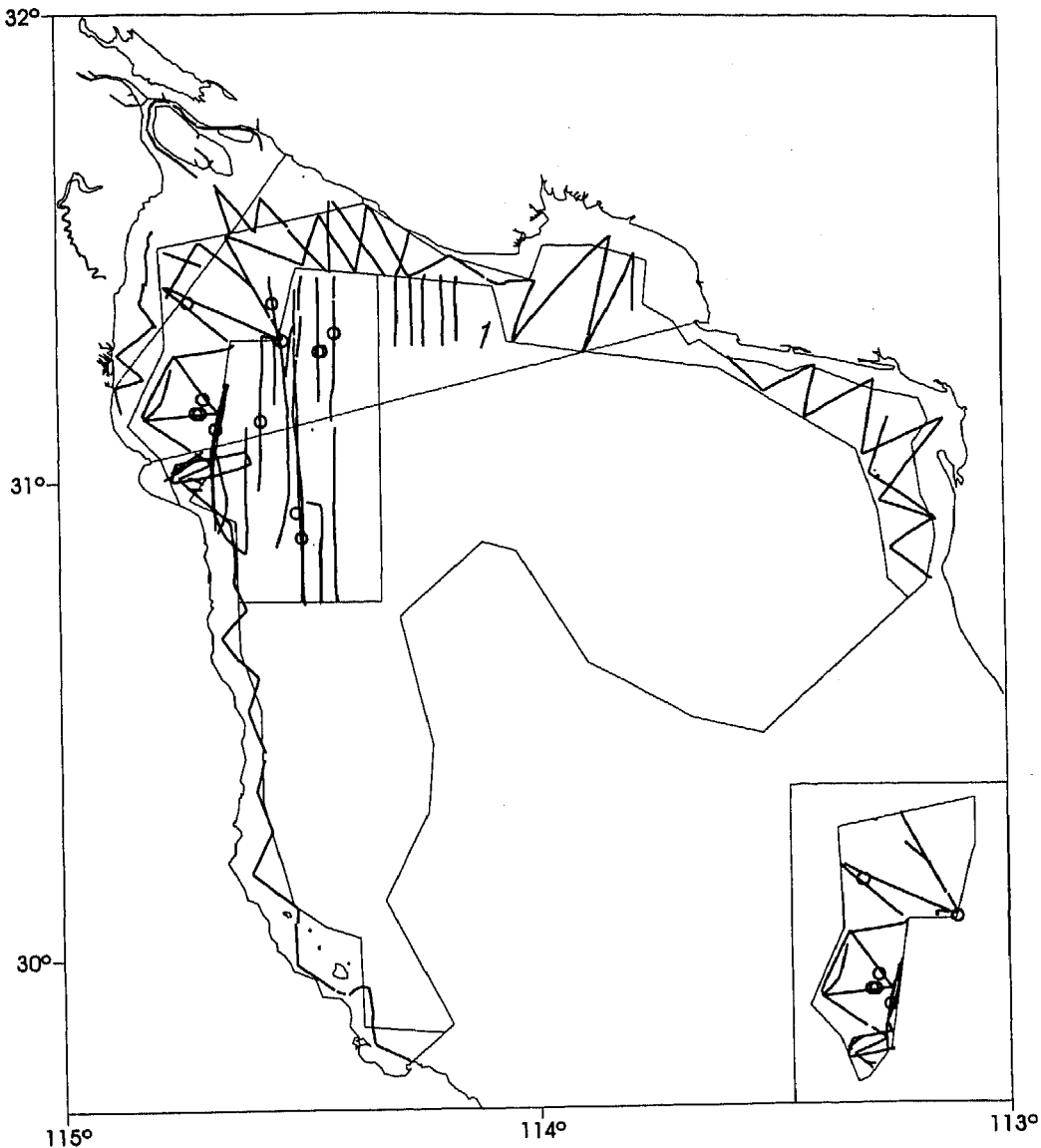


Figure 5. Total survey effort (thin lines) and sightings (circles) aboard *BIP XI* (solid line) and panga (broken line west of sub-area and near mouth of Colorado River). All shallow-water vaquita sightings occurred in post-stratified sub-area indicated in lower right.

veys reported here were the first specifically designed to estimate the abundance of *Phocoena sinus* over the whole range of the species. The results are important for management decisions affecting the species and for evaluating threats to the population (Rojas-Bracho and Taylor 1999), especially mortality in fishing nets (Vidal 1995; D'Agrosa *et al.*, in press). In general, the results confirm earlier studies that the vaquita population is small and limited to an area in the northwestern Gulf of California.

The 1997 estimate of vaquita abundance is an improvement over previous estimates, which suffered from low numbers of sightings, relied on parameters taken from other species, and/or did not cover all areas where vaquitas could

potentially be found (Barlow *et al.* 1997). The current study achieved a large number of sightings, covered the entire range of the species, and did not rely on information taken from other studies. Nevertheless, the current estimate is the middle of the range of previous estimates, lending support to the whole group of studies. Taken together, the studies indicate that the population is small, isolated, localized, and in danger of extinction.

The current estimate of 567 is considerably higher than the 1993 estimate of 224 vaquitas. While the higher estimate is encouraging, the numbers are not directly comparable for several reasons. First, the areas surveyed in 1993 and 1997 were not the same. In particular, the 1993 study did not cover the shallow sub-area that the current study indicated is an area where significant numbers of vaquitas may be found. Second, the estimate of $g(0)$ from the 1997 survey was lower than the value assumed for the 1993 estimate, which was taken from harbor porpoise surveys. If the present value of $g(0)$ had been used for the 1993 analysis, the estimate of vaquita abundance would have been 311 in 1993, which is not very different from the 409 estimated in this report, given the variances. Finally, the 1997 survey represented a substantial increase in effort, and produced a better estimate of population size. Therefore, without further analysis, a direct comparison of the 1993 and 1997 estimates is not meaningful, and the results do not mean that the vaquita population has increased, or is increasing, in size.

Although there is no estimate of total annual fishing mortality, the data that do exist indicate clearly that mortality due to gillnet fishing is a threat to the population (Rojas-Bracho and Taylor 1999). D'Agrosa *et al.* (in press) estimated vaquita mortality as 83 vaquitas/year in 1993–1994 in one of three fishing towns in the area, based on direct observation. This rate alone represents 14% of the 1997 population estimate and is unlikely to be sustainable, but it does not include any mortality from the other fishing towns. Total annual mortality due to gillnets, although unknown, is therefore expected to be large enough to cause the vaquita population to decline.

The coefficient of variation of the total abundance estimate was rather high (0.51, Table 1). This was mainly due to the low number of sightings by 7× binoculars, which led to low numbers of sightings both on the *DSJ* bridge for $g(0)$ estimation and on the *BIP* for $f(0)/g(0)$ estimation, and consequently high variance for those estimates. The CV was also high due to a highly variable sighting rate.

Detecting Vaquitas

The total number of vaquita groups seen during this study (125) was more than all previous studies combined. This was primarily due to the use of the large 25× binoculars and greater viewing height on the *DSJ*. A small number of sightings has been the primary limitation of past attempts to collect quantitative information on vaquita abundance. Transects conducted on boats on which sighting height was 6 m or less, and on which searching was done by eye or with hand-held binoculars, have always had very little success in de-

tecting vaquitas (Wells *et al.* 1981, Vidal *et al.* 1987, Silber 1990, Fleischer and Pérez-Cortés: PNICMM sightings in Gerrodette *et al.* 1995, Villa Ramírez: IBUNAM sightings in Gerrodette *et al.* 1995). During the present study, observers on the *BIP* and the *DSJ* bridge used hand-held binoculars and also had low sighting rates.

This study indicated that the reason for the low number of sightings in past studies was the low probability of finding vaquitas by eye or with hand-held binoculars. Using the 25 \times binoculars at 10.7 m on the *DSJ* was seven times as effective as using 7 \times binoculars at a height of 6.3 m on the *BIP*, based on a comparison of the $f(0)/g(0)$ ratios of the two ships. The simple ratio of the encounter rates in the core area showed a similar value (0.107/.016=6.8). The viewing height on the *BIP* was higher than in the previous studies cited above, so it is likely that the efficiency of those earlier studies was even lower, and this would explain the low number of sightings. The analysis of movement (Fig. 3) showed that vaquitas tend to move away from the path of the vessel at a distance of about 900 m. Since the area being effectively searched by 7 \times binoculars and by eye is less than 900 m, few vaquitas will be seen. Most will move away to a distance at which the probability of detection is low. It is clear that future visual surveys should utilize a large vessel with 25 \times binoculars. In shallow water, where smaller shallow-draft vessels must be used, the use of 25 \times binoculars, if possible, would probably increase the detection rate significantly.

The parameter $g(0)$ was estimated from a two platform survey design on the *DSJ*, although the sample size of the bridge data set was small. The results indicated that only somewhat over half (57%) of vaquita groups on or near the trackline were detected from the flying bridge by a team of three observers with 25 \times binoculars under calm conditions, emphasizing once again how difficult vaquitas are to detect. Observers on the *DSJ* bridge with 7 \times binoculars detected only 15% of vaquita groups on or near the trackline. The parameter $g(0)$ was not estimated directly for the *BIP*. However, if we assume a reasonable effective strip half-width [$1/f(0)$] of 500 m for the *BIP*, based on bridge *DSJ* sightings and values used in Barlow *et al.* (1993), this implies $g(0) = 0.28$. This is nearly twice the value estimated for observers on the *DSJ* bridge, which is higher than the flying bridge of the *BIP*. Nevertheless, we consider the higher implied $g(0)$ for the *BIP* reasonable. From 15–16 September, the *BIP* and *DSJ* were working in calm conditions in the core area close to one another. During this time, three sightings were made from the *BIP*, while only one was made from the bridge of the *DSJ*, resulting in an encounter rate for the *BIP* more than twice that from the *DSJ* bridge. A possible reason for this difference is that the *BIP* is a shrimp trawler, a common type of fishing boat in the upper Gulf, and vaquitas may avoid this vessel less strongly than the larger *DSJ*.

Aggregation and Distribution

One factor that had a major effect in the survey was the aggregating behavior of vaquitas. The high variance in the encounter rate demonstrated the

effect of this behavior. On a single day, 17 September, near the end of the cruise, 41 vaquita groups (37% of the total for the whole cruise) were detected in a few hours. Whether such an aggregation of groups is encountered or not on a survey obviously has a strong effect on the analysis. If this aggregation had been encountered during the 1993 survey, the estimate would have been quite different. If the September 17 data were removed, the 1997 encounter rate would decrease 45% and group size would decrease 6%. It is clear that the data from this day were important not only for increasing sample size for $f(0)$ estimation, but for encounter rate and abundance estimation as well. Such extreme aggregation indicates the importance of obtaining large sample sizes to estimate abundance.

There is some indication that shrimp trawlers are related to aggregation of vaquitas. We observed aggregation after the shrimp fleet (trawling and gill nets) began operations in early September. No large aggregations were observed before that, nor were large aggregations observed on the 1993 cruise, which took place before the shrimping season started. In any case, whether caused by shrimp trawlers or not, the aggregation of vaquitas, together with the aggregated nature of the artisanal shrimp gill net fleet, makes the population vulnerable to a single large mortality event.

The estimated density of vaquitas in the shallow sub-area (Fig. 5) was 77% of the estimated density in the core area. Thus, this area to the north of the town of San Felipe and less than 20 m deep appears to be more important vaquita habitat than previously thought, at least during August and September. An acoustic survey in April 1997 also encountered vaquitas in the core area close to San Felipe, but not in the Colorado River Delta area (AJL and LRB, unpublished data). The scarcity of previously reported sightings in the shallow area north of San Felipe is due to low search effort (Silber 1990, Silber and Norris 1991, Barlow *et al.* 1997) in combination with the low sighting efficiency of boats able to navigate in the shallow water. Acoustic surveys (Chappell *et al.* 1996) show great promise for vaquita studies, because an acoustic detector can be used from a small boat in shallow water and is less dependent on calm weather conditions than visual surveys.

The results of this survey support previous conclusions (Gerrodette *et al.* 1995) that vaquitas are found only on the western side of the upper Gulf of California. No vaquitas were encountered in the delta area near the mouth of the Colorado River, nor in the surveyed areas to the south, north, and east of the core area. The results of this survey further indicate that the boundaries of the Upper Gulf of California and Colorado River Delta Biosphere Reserve, which is supposed to provide protection for vaquitas, do not correspond well to the distribution of vaquitas. Forty percent of the 1997 sightings were outside the reserve boundary (Fig. 2, 5), and no sightings were within the nuclear zone of the reserve, which is the area where all fishing is prohibited. Therefore, for adequate protection of vaquitas, new boundaries and new regulations should be considered.

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