Cosco Busan Oil Spill NRDA: Herring Injury Quantification

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Overview

This document describes the Trustees' approach for quantifying the impacts of the *Cosco Busan* oil spill on the eggs of Pacific herring (*Clupea pallasi*) during the 2007-2008 spawning season.

Field and laboratory studies of herring embryos after the spill produced two main findings. First, exposure to *Cosco Busan* oil produced embryo abnormalities also seen in previously published studies of effects of crude oil on developing fish embryos (Carls *et al.* 1999, Heintz *et al*. 1999, Incardona *et al*. 2008a). These abnormalities are expected to result in fish mortality at an early life stage. Field studies during the first spawning season after the November 2007 *Cosco Busan* spill found increased occurrences of pericardial edema in caged herring eggs placed in subtidal water adjacent to shoreline oiling. The oiling classifications (e.g., heavy oiling, light oiling, very light oiling) were based on oiling documented by spill responders for the purpose of setting cleanup priorities. However, field study results did not vary by "degree of oiling", but rather by the identification of the presence or absence of oil (Incardona *et al.* 2008b).

Second, toxicity of *Cosco Busan* oil was enhanced by the presence of ultraviolet (UV) radiation. Naturally spawned herring eggs collected from shallow areas of oiled sites in 2008 showed gross abnormalities and necrosis not seen in eggs collected from shallow areas at a reference site (Incardona *et al.* 2008b). Laboratory studies conducted in 2009 (Incardona *et al.* 2009) demonstrated that exposure of eggs to very low concentrations of *Cosco Busan* oil in the presence of sunlight led to high rates of embryonic death.

The Trustees developed an estimate of herring loss across the entire 2007-2008 spawning season using information and conclusions from post-spill studies (Incardona *et al.* 2008b; Incardona *et al.* 2009; Incardona *et al.* Forthcoming) and data on spawning intensity (CDFG Aquaculture and Bay Management Project, unpublished data). This required the examination of three factors that drive the estimate:

1. Impacts of Exposure. This is the percentage of eggs expected to exhibit lethal abnormalities when exposed to *Cosco Busan* oil.

2. Exposure by Substrate and Depth. This is the relationship between the degree of exposure and number of eggs exposed on three habitat types where herring spawn was found in the 2007-2008 season: (1) shoreline rocks and vegetation; (2) submerged vegetation, and (3) vertical "manmade" structures.

3. Locations of Exposure. These are geographic locations where exposure to *Cosco Busan* was expected to occur based upon the convergence of shoreline oiling observations and herring spawning locations.

All three of these components are evaluated in terms of both upper- and lower-bound estimates. The result is a range of estimates that bracket the percentage of eggs expected to exhibit lethal abnormalities associated with exposure to *Cosco Busan* oil. Some percentage of these eggs would have failed to result in viable larvae due to other natural occurrences (e.g., anoxia, wave action, desiccation, consumption) under both spill and baseline conditions.

Based on the findings of Incardona *et al*. Forthcoming, the Trustees assumed: (1) injury occurred in the 2007/8 spawning year, and (2) viability of spawn in subsequent years was not significantly affected.

Impacts of Exposure

Estimated impacts of oiling are based upon field studies described in Incardona *et al*. (2008b). Field observations conducted just prior to hatching include a combination of background mortality and oil-related impacts. Our primary approach for isolating the rate of oiling impacts utilizes the following equation:

$$1 - r_T = (1 - r_B)(1 - r_o) \qquad (1)$$

The proportion of eggs remaining viable to hatch in oiled areas ($1 - r_T$) is the proportion viable under baseline conditions ($1 - r_B$) multiplied by the proportion unaffected by oil ($1 - r_o$). This provides a consistent framework for handling the full range of impacts (i.e., r_o and r_B between 0 and 1, inclusive) while still maintaining feasible bounds for total mortality (i.e., r_T between 0 and 1, inclusive).[1] Rearranging Equation (1) yields our estimate of proportion or rate of oil effects.

$$r_o = \frac{r_T - r_B}{1 - r_B} \qquad (2)$$

In the vicinity of shoreline oiling, herring eggs artificially caged in deeper water demonstrated fewer abnormalities than herring eggs collected in shallow waters. Incardona *et al*. (2008b) hypothesize that these differences result from varying exposures from UV radiation at depth. Consistent with these results, we parameterize Equation (2) separately for spill impacts at shallow depths (based upon natural spawn studies) versus impacts in deeper waters (based upon caged spawn studies). Specific depths associated with each study will be discussed in the next section.

Shallow Water Impacts (Natural Spawn Studies)

Natural spawn samples that were taken from areas adjacent to shoreline oiling exhibited low rates of normal hatch (Incardona *et al*. 2008b). Averaging across three samples near oiled sites (embryos: n = 670, 529, 425), the mean rate of abnormalities was 95%. These abnormalities

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[1] Some deposited eggs ($r_B r_o$) would be affected by both oil and baseline conditions. When assessing the marginal impact of the spill above baseline conditions, this overlap would need to be addressed.

were expected to result in the death of the embryo. A single reference sample was taken outside the spill zone. Of the 518 embryos evaluated in that sample, 26% exhibited abnormal hatch. Applying these rates for r_T and r_B (respectively) yields an oil-specific rate (r_o) of 93%.

Incardona *et al*. (2008b) note that egg masses at non-oiled sites were thicker (approximately four layers) than the egg masses at the oiled sites (approximately one layer). Egg mass thickness is known to increase hatch failure (Taylor 1971, Alderdice and Hourston 1985). Samples of four layer egg masses spawned in natural conditions, as described in Taylor (1971), had an average failure rate ranging from 14 to 28%, with an average of 22%. This is similar to what was found in the non-oiled natural spawn samples. The lightest natural spawn evaluated by Taylor (1971) was two layers thick. Failure at this egg mass density ranged from 7% to 22%, with an average of 15%. It was hypothesized that even lower failure rates would occur when egg masses were one layer thick (Taylor 1971). The implication is that the 26% failure rate at natural spawn sites outside the spill area is likely to overestimate background ("non-oiling") failure rates of the less dense egg masses in the oiled natural spawn study areas.

Fortunately, this has little practical importance for estimating the rate of oil-related mortality (r_o) at the natural spawn sites. Oil-related mortality rate is already bounded by the total mortality rate estimate of 95%. Even assuming that the background mortality of the natural spawn was significantly lower than 26%, an oil-related mortality rate of 93% can only increase by 2% before reaching the upper bound. For the purpose of injury quantification, we consider the upper and lower bounds for shallow water impacts to be 95% and 93%, respectively.

Deeper Water Impacts (Caged Spawn Studies)

Overall, caged spawn samples that were taken from areas adjacent to shoreline oiling also displayed lower rates of normal hatch than areas outside the spill zone (Incardona *et al*. 2008b). Averaging across estimates from four caged spawn samples in the spill zone, the mean rate of abnormalities was 15.9% (embryos: n = 583, 401, 236, 535). The average rate of abnormalities from two samples taken outside of the spill zone was 9.4% (embryos: n = 345, 258). Applying these rates for r_T and r_B (respectively) yields an oil-specific mortality rate (r_o) of 7.3%.

While there is an aggregate difference in abnormality rates displayed by the 1755 embryos sampled adjacent to oiled sites and 603 embryos sampled at unoiled sites, there is significant heterogeneity between the samples in each category (Incardona *et al*. 2008b). Differences between the two control locations are particularly noteworthy. This variation makes it prudent to evaluate alternatives to the 7.3% estimate of loss in deeper waters.

A more conservative approach of identifying oil-related mortality is to focus on abnormalities that are known to be associated with oil exposure, that were only found in the samples taken adjacent to oiled shorelines. Specifically, we looked at the mean rate of pericardial edema, which had an average rate of occurrence of 1.6% in the four caged spawn samples taken adjacent to shoreline oiling. Embryos with these abnormalities are not expected to develop into viable larvae, and there were no occurrences of pericardial edema in the control sites (0%). Using this 1.6% estimate as a direct measure of r_o assumes that the increased aggregate rate of all other abnormalities result from other causes.

For the purpose of injury quantification, we consider the upper and lower bounds for deeper water oil impacts to be 7.3% and 1.6%, respectively.

Exposure by Substrate and Depth

Surveys of herring egg deposition around San Francisco Bay are conducted annually by the California Department of Fish and Game (CDFG). Methods are delineated by three general categories of substrates: (1) shoreline rocks and vegetation; (2) submerged vegetation, and (3) vertical "manmade" structures. These historical data were obtained by the Trustees for the purpose of their injury analysis (CDFG Aquaculture and Bay Management Project, unpublished data). To match estimates of egg deposition to rates of abnormalities, egg deposition on each class of substrate is evaluated in the context of the field study results.

Shoreline Rocks and Vegetation

The natural spawn samples from the Incardona *et al*. (2008b) studies were taken on substrates that would be classified as shoreline rock and vegetation under the CDFG procedures for estimating egg deposition. With limited exception (e.g., accessibility), egg quantification for shoreline rock and vegetation focuses on areas that are visible from above the water line at the time egg deposition is assessed (Bartling, pers comm.). When focusing on geographic locations where eggs are exposed to oil, we would therefore expect herring eggs to be subject to the combined effects of light and oil. Thus, all "shoreline rocks and vegetation" areas are considered to be shallow and likely subject to the higher oil-related abnormality rates.

Ranges of Exposure Depth: Submerged Vegetation and Vertical Structures

Unlike quantified egg deposition on shoreline rocks and vegetation, the deposition estimates for submerged vegetation and vertical structures are based upon extrapolation to locations beneath the depths were the deleterious effects of oil are expected to occur. To identify vertical breakpoints to use for the higher impact (shallow) and lower impact (deeper) categories, we use information about the depth that eggs were exposed to oil in the natural spawn and caged spawn studies, respectively.

Egg collections for the shallower (greater impact) natural spawn studies were conducted when the tide was between +1.5 feet and +0.8 foot mean lower low water (MLLW) (Incardona *et al*. 2008b). At the time of sampling, eggs were taken at depths that ranged from just below the tide level to as much as two feet below the tideline (Myers, pers comm.). For the purpose of quantifying exposure on submerged vegetation and vertical structures, the deepest possible exposure depth for the natural spawn studies is the subtraction of the maximum depth of sampling (2 feet below tideline) from the lowest tide where sampling occurred (+0.8 foot MLLW). This is –1.2 feet MLLW. The lower bound on depth of exposure is derived from the observation that the shallowest exposure for eggs collected two feet below the waterline is –0.5 foot MLLW. We use this –0.5 to –1.2 foot MLLW range to describe the lower and upper bounds for the deepest vertical extent of the upper impact category.

Egg exposure during the deeper (less impact) caged spawn studies occurred in cages that were suspended in the water column. These cages were placed at locations where the bay bottom was between -3 and -6 feet MLLW (Incardona *et al.* 2008b). The cages themselves, however, were suspended one to two feet above the bay floor (Myers, pers comm.). The deepest exposure of the caged spawn studies is derived by adding between one and two feet to the depth of the deepest locations (-6 feet MLLW) where cages were placed. This yields a –4 to –5 foot MLLW range describing the lower and upper bounds for the deepest vertical extent of the lower impact category. No injuries are assumed below these depths.

Submerged Vegetation

Estimates of herring egg deposition on submerged vegetation combines the observed spatial extent of specific spawning incidents with the estimated average egg deposition intensity within those boundaries. To quantify eggs subject to each exposure depth category, we combined number of eggs estimated in each discretely identified incident with the bathymetry of the underlying bay floor.

Spawning boundaries obtained from the CDFG Herring Unit were overlaid with the National Oceanographic and Atmospheric Administration (NOAA) 30m resolution bathymetric digital elevation model of San Francisco Bay (NOAA 1998). Centroids of the raster image that fell within the spawning polygon were evaluated based upon their depth category. The percentage of eggs assigned to each injury category (for each individual spawning event documented during the season) was proportional to the percentage of grid depths that fell in the higher injury region (i.e., shallow spawn above either -0.5 foot or -1.2 feet MLLW) and lower injury region (i.e., deeper spawn down to -4 feet to -5 feet MLLW), adjusted for alternative assumptions regarding the height of submerged vegetation (Figure 1).[2]

Accounting for the height of submerged vegetation involves shifting the exposure depth from the bathymetry of the bay floor to shallower depths in the water column. The longer the vegetation used as spawning substrate, the more likely it is that eggs will be suspended higher into the water column and therefore subject to the more deleterious effects of the interaction between oil and light. To create an upper bound for the eggs subject to exposure, we assumed that the spawn extended two feet up into the water column, with the density of that spawn at any given point being evenly distributed by depth. This is based upon the typical height that *zostera* sp (eelgrass) extends up into the water column in San Francisco Bay (Bartling pers comm.). To create a lower bound, we assumed this length was six inches, consistent with the height of *gracilaria* sp (Bartling pers comm.). The quantitative implications of accounting for the length of vegetation is that eggs deposited at a given geographic location were able to fall in more than one injury category (e.g., high injury, lower injury, no injury) if the vegetation was expected to span more than one depth range.

Vertical Structures

CDFG estimates herring egg deposition on vertical waterfront structures by combining measurements of the surface area of specific structures with estimates of the thickness and depth of spawn. To quantify the number of eggs that falls within each injury category, we separated the total depth of spawn on each individual structure into depths where we would expect greater injury (i.e., above either -0.5 foot or -1.2 feet MLLW, depending upon scenario), depths where we would expect lower levels of injury (i.e., spawn down to -4 feet to -5 feet MLLW), and

[2] Since the bathymetry coverage used for this analysis was based on mean low water (MLW) versus MLLW, all depths were adjusted by -1.1 feet. Near shore polygons that were missing from the bathymetric database were assumed to fall completely in the “shallow” (or higher injury) depth category.

greater depths where we would expect no injury (Figure 2). Consistent with the assumptions used to quantify total egg deposition by the CDFG herring unit, we assumed that the thickness of spawn is constant across depth categories.

Our expectation is that herring spawn up to the high water mark. To quantify the number of eggs above the 0 foot MLLW, we needed to develop an estimate of an effective high water at the time of spawn. An upper bound for this highest spawn highest tide is the highest tide height during the estimated date of spawn. For a lower bound, we use the average water level on that day.

Geographic Locations with Exposure to Oil

Spill response and damage assessment personnel visually identified sites around the bay where *Cosco Busan* oil stranded on shoreline. Concentrations of oil below what one might expect to be observable through visual reconnaissance are expected to produce lethal abnormalities (Incardona *et al.* Forthcoming). This implies that there is some uncertainty regarding the extent to which visual observations of oiling will adequately characterize locations where exposure to oil occurred. We bound this uncertainty by exploring two scenarios of impacts: one which focuses narrowly on the site by site visual observations of oil in close proximity to surveyed spawning activity (i.e., a lower impact scenario), and one that attributes impacts more broadly to entire spawning events occurring within the broad geographic area where shoreline oiling was observed during the spill (i.e., a higher impact scenario). Table 1 summarizes the locations used in each scenario by geographic area. Figures 3 and 4 provide maps of these locations for vertical shoreline structures and other substrates, respectively.

Estimated egg deposition by substrate type and location for both upper and lower impact scenarios is presented in Table 2. When examining a broad geographic extent of potential egg exposure (the higher impact scenario), we estimated that 437.6 billion eggs (49.8% of the total season's spawn) were deposited in areas where egg impacts could have occurred. This is reduced to roughly half (226.2 billion, 25.7% of season's spawn) when using a narrow geographic definition (the lower impact scenario).

Results

We combine assumptions (see Table 3) regarding the location of the egg deposition, estimated depth of deposition, and impacts at depth to generate an estimate of the number of eggs subject to lethal oil-related abnormalities (Table 4).[3] In the high exposure scenario, we estimate 29.1% of the spawn (255.9 billion eggs) is expected to be subject to lethal, oil-related abnormalities. In the low exposure scenario, this estimate is 13.5% (118.8 billion eggs).

[3] See Appendix A for greater detail on the egg deposition estimate by substrate, date, and location, along with the estimated percentage of eggs exposed under the upper bound (higher impact) and lower bound (lower impact) scenarios.

General Caveat

The above analysis examines impacts of *Cosco Busan* oil on Pacific herring eggs deposited on spawning substrates during the 2007-2008 season. The main output of the analysis is the percentage of eggs subject to lethal abnormalities. This calculation first examines the number of eggs in both high and low exposure categories and then multiplies these numbers by the respective rates that lethal abnormalities are expected to occur.

Cosco Busan oil is not the only agent that causes deleterious effects on early life stages of herring. Herring are subject to a number of other factors that can prevent the development of eggs to viable larvae, and ultimately, adult fish. At a minimum, these include wave action, predation, desiccation, and other sources of substrate contamination. This "background" mortality affects eggs both inside and outside the spill area. To the extent that these factors have similar effects on the numerator (i.e., number of eggs affected) and denominator (total number of eggs) in our percentage egg loss calculation, they do not affect our ability to transfer results from the above analysis to better understand total percentage losses to the 2007-2008 cohort over time.

However, if one accepts the premise that sources of background mortality vary by spawning substrate (e.g., shoreline rocks and vegetation, submerged vegetation, vertical structures), it is reasonable to assume that full impact of the spill on the 2007-2008 herring cohort over time can be either greater than or less than the percentage ranges of eggs affected that are described in this document. This is because the distribution of spawn substrate in oil-affected areas does not perfectly match the distribution of substrate utilized by all spawning herring in the 2007-2008 season.

For example, in the upper-bound scenario, there is a similar percentage of spawn on submerged vegetation within the spill areas to the percentage spawn on submerged vegetation across the entire spawning season. However, the percentage of spawn on shoreline rocks and vegetation within the spill area is lower than the percentage of spawn on shoreline rocks/vegetation season-wide. The extent to which the 29.1% upper-bound estimate of eggs affected by the spill either overestimates or underestimates the *percent loss* to the 2007-2008 cohort over time largely depends on baseline success of larvae deposited on shoreline rock/vegetation versus the success of larvae vertical structures.

In the lower-bound scenario, the share of spawn on shoreline rocks/vegetation and vertical structures within the spill areas are similar to the percentage shares on these substrates season-wide. However, since these substrates already account for almost 88% of the total spawn in 2007-2008, the fact that both are somewhat over-represented translates to a large proportional reduction in the share of spawn on submerged vegetation within the areas (and depths) affected in the lower-bound spill scenario. If one assumes that spawn on submerged vegetation is more successful than spawn on other substrates, the 13.5% lower-bound estimate of eggs affected by the *Cosco Busan* oil has the potential to overestimate the lower-bound impact of the spill on the 2007-2008 cohort over time. The effect of this overestimate is limited by the fact that spawn on submerged vegetation is only a small percentage of the total spawn (12%).

In short, how one interprets these shifts in substrate distribution across scenarios depends on the relative weights of spawning success assigned to each substrate type. Rather than further developing models to assign losses by substrate medium and completing a full quantitative exercise of restoration scaling, the trustees opted instead to focus their resources and efforts on the exploration of feasible restoration options.

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Table 1: Locations where Exposure Quantified

Location	Higher Impact (Upper Bound) Scenario	Lower Impact (Lower Bound) Scenario
Richardson Bay and Vicinity	*Shoreline rocks and vegetation* • Richardson Bay shoreline • Belvedere shoreline • Point Diablo *Submerged vegetation* • Entire Richardson Bay • Keil Cove *Vertical Structures* • Entire Richardson Bay waterfront	*Shoreline rocks and vegetation* • Richardson Bay shoreline • Belvedere shoreline *Submerged vegetation* • Nearshore Richardson Bay • Keil Cove *Vertical Structures* • Clipper Yacht Harbor • "Dunphy Park" marinas
North San Francisco waterfront	*Shoreline rocks and vegetation* • All spawn from Marina Green Yacht Club to Pier 45 *Vertical Structures* • All spawn from Marina Green Yacht Club to the "Ferry Pier" west of Pier 41	*Shoreline rocks and vegetation* • Fort Mason shoreline • Aquatic Park shoreline • Shoreline by fuel dock east of Aquatic Park *Vertical Structures* • Fort Mason Center • Municipal Pier • Pier 45 and adjacent sea wall • "Ferry Pier" west of Pier 41
East San Francisco waterfront	*Shoreline rocks and vegetation* • South Beach riprap wall *Vertical Structures* • San Francisco waterfront wall to "The Ramp"	*Shoreline rocks and vegetation* • South Beach Riprap Wall *Vertical Structures* • San Francisco waterfront wall • "Ruins Pier"

Table 2: Eggs in Geographic Areas Considered to be At-Risk Areas (billions)

Location	High Exposure Scenario	Low Exposure Scenario
Shoreline Vegetation and Rocks		
Richardson Bay and Vicinity	7.38	6.23
SF Waterfront, North	121.78	91.24
SF Waterfront, East	3.76	3.76
Lower Intertidal and Subtidal Vegetation		
Central Richardson Bay	52.45	0.00
West Richardson Bay	7.88	7.88
Kiel Cove	0.72	0.72
Piers/Pilings/Seawalls		
Richardson Bay	20.16	1.91
SF Waterfront, North	116.84	109.89
SF Waterfront, East	106.60	4.59
Total (billions)	437.56	226.22
% of Total Spawn Estimate	49.8%	25.7%

Table 3: Overview of Assumptions in Upper-Bound and Lower-Bound Impact Scenarios

Input	Higher Impact, Upper-Bound	Lower Impact, Lower-Bound
Percent oil-related abnormalities – shallow areas	95%	93%
Percent oil-related abnormalities – deeper areas	7.3%	1.6%
Depth of shallow water impacts	Above -1.2 feet MLLW	Above -0.5 foot MLLW
Depth of deeper water impacts	Down to -5 feet MLLW	Down to -4 feet MLLW
Extension of vegetation upwards into the water column (submerged vegetation only)	2 feet	6 inches
High water mark (vertical structures only)	Highest tide on estimated date of spawn (6.17 to 6.56 feet MLLW)	Average tide on estimated date of spawn (2.97 to 3.53 feet MLLW)
Spatial Extent (see Table 1)	Majority of spill area	Submerged vegetation in Keil Cove and nearshore Richardson Bay; Shoreline rocks, vegetation, and vertical structures primarily on the northern San Francisco waterfront

Table 4: Expected Eggs Subject to Oil-Related Abnormalities (billions)

Location	High Exposure Scenario	Low Exposure Scenario
Shoreline Vegetation and Rocks		
Richardson Bay and Vicinity	7.01	5.80
SF Waterfront, North	115.69	84.85
SF Waterfront, East	3.58	3.50
Lower Intertidal and Subtidal Vegetation		
Central Richardson Bay	10.59	0.00
West Richardson Bay	2.64	1.86
Kiel Cove	0.30	0.05
Piers/Pilings/Seawalls		
Richardson Bay	11.29	0.51
SF Waterfront, North	44.72	20.18
SF Waterfront, East	60.07	2.07
Total (billions)	255.87	118.82
% of Total Spawn Estimate	29.1%	13.5%

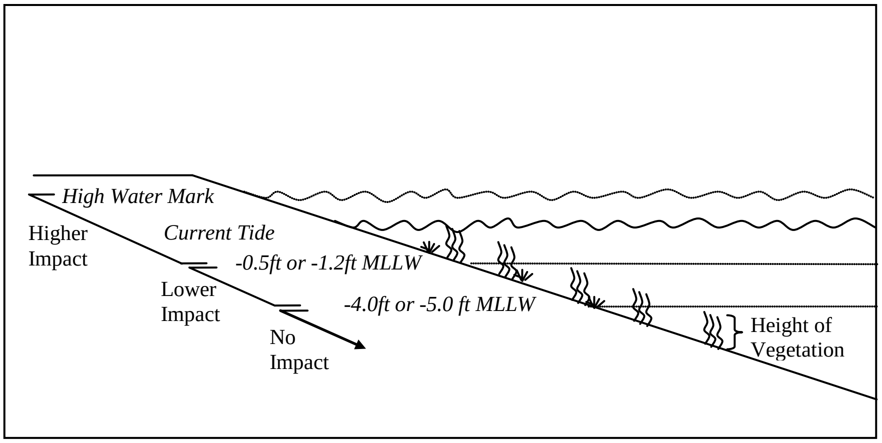


Figure 1: Application of Data from Herring Embryo Field Studies to Spawning Impacts on Submerged Vegetation.

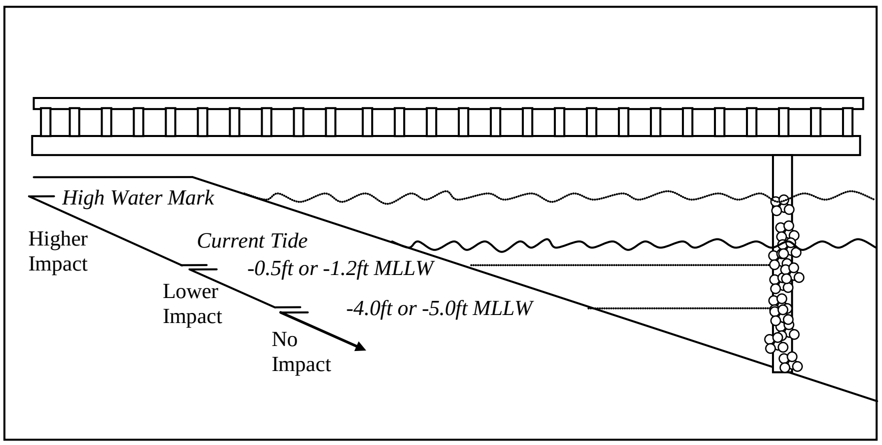
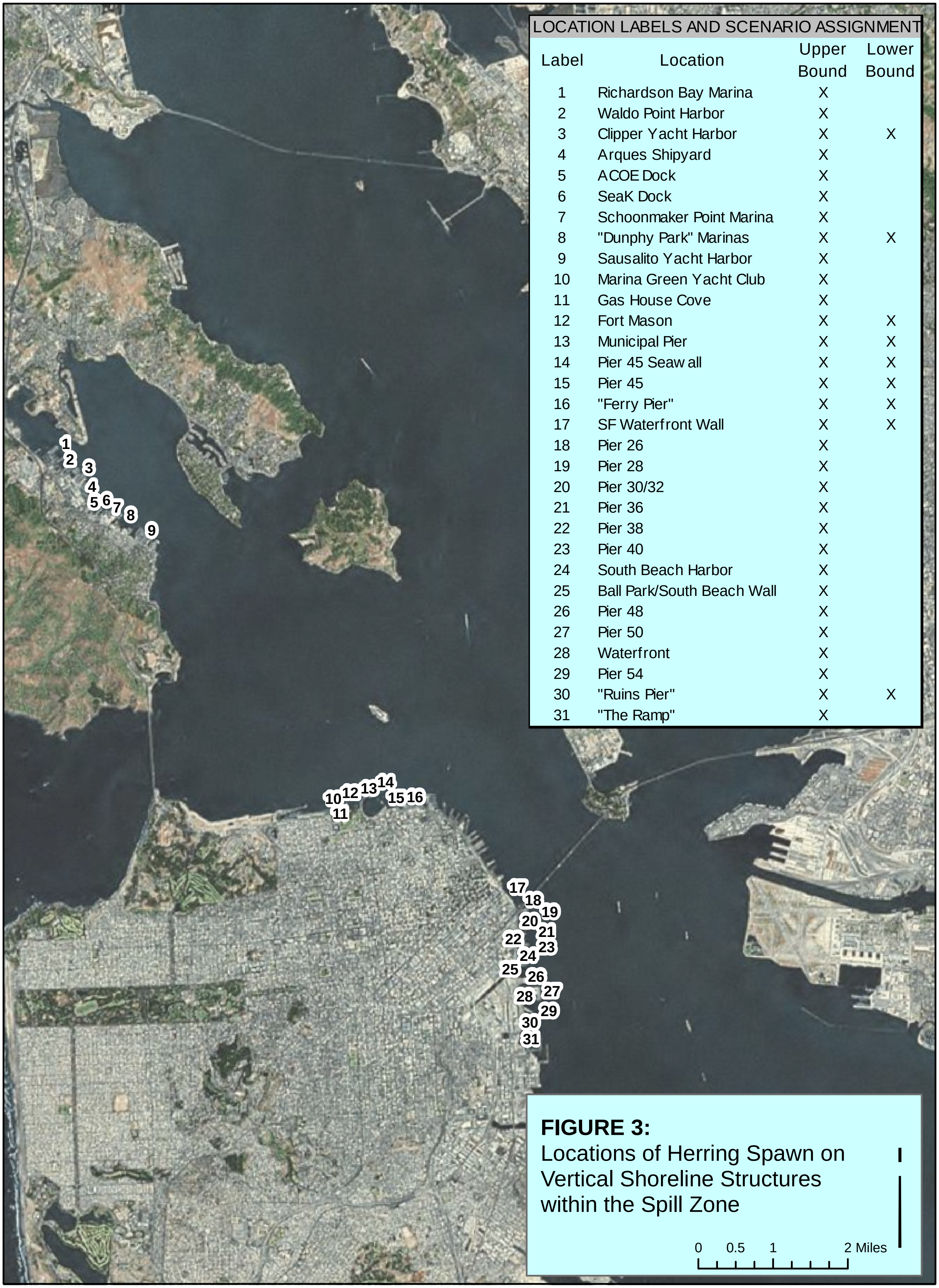


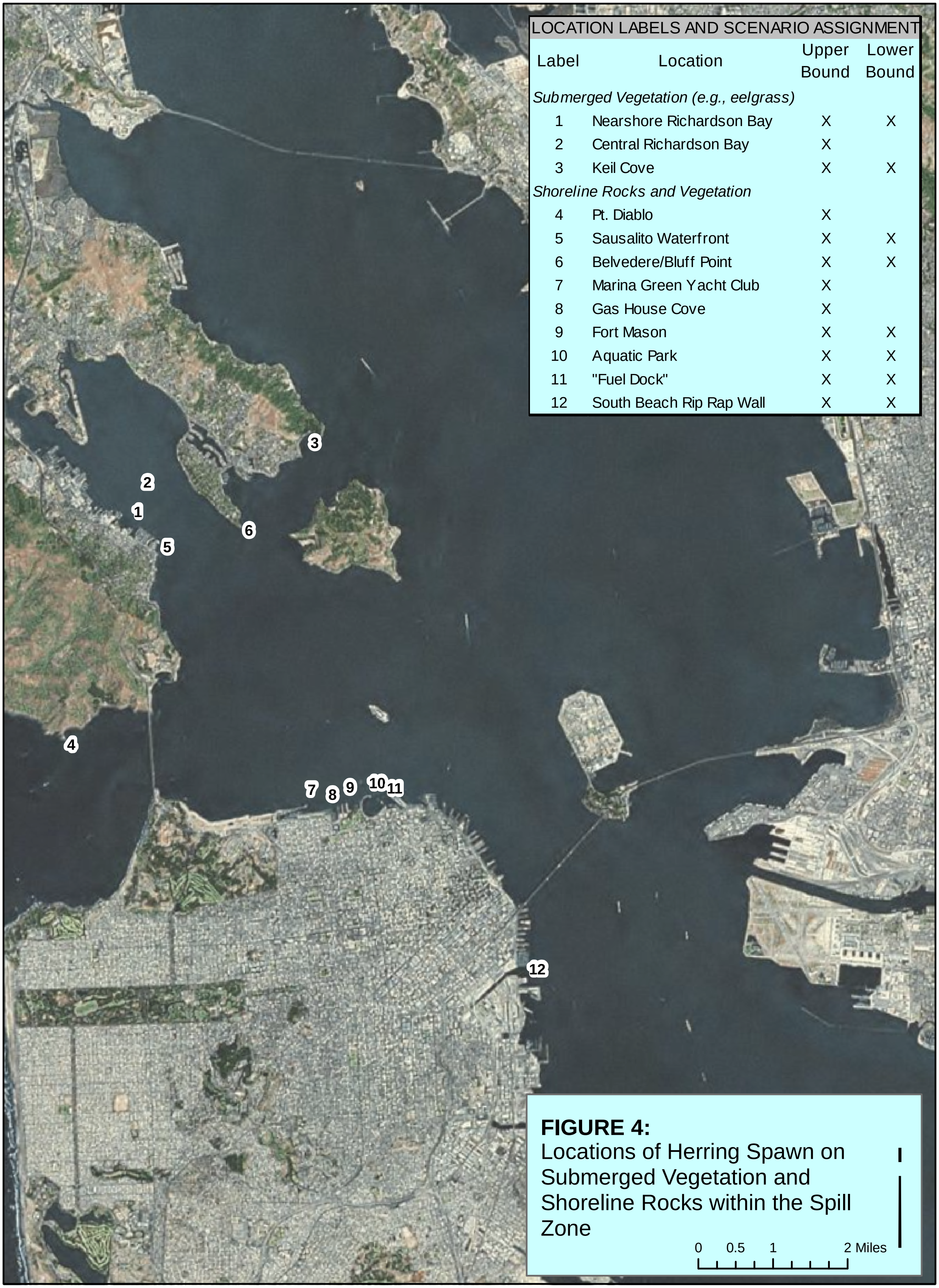
Figure 2: Application of Data from Herring Embryo Field Studies to Spawning Impacts on Vertical Structures.



LOCATION LABELS AND SCENARIO ASSIGNMENT

Label	Location	Upper Bound	Lower Bound
1	Richardson Bay Marina	X	
2	Waldo Point Harbor	X	
3	Clipper Yacht Harbor	X	X
4	Arques Shipyard	X	
5	ACOE Dock	X	
6	SeaK Dock	X	
7	Schoonmaker Point Marina	X	
8	"Dunphy Park" Marinas	X	X
9	Sausalito Yacht Harbor	X	
10	Marina Green Yacht Club	X	
11	Gas House Cove	X	
12	Fort Mason	X	X
13	Municipal Pier	X	X
14	Pier 45 Seaw all	X	X
15	Pier 45	X	X
16	"Ferry Pier"	X	X
17	SF Waterfront Wall	X	X
18	Pier 26	X	
19	Pier 28	X	
20	Pier 30/32	X	
21	Pier 36	X	
22	Pier 38	X	
23	Pier 40	X	
24	South Beach Harbor	X	
25	Ball Park/South Beach Wall	X	
26	Pier 48	X	
27	Pier 50	X	
28	Waterfront	X	
29	Pier 54	X	
30	"Ruins Pier"	X	X
31	"The Ramp"	X	

FIGURE 3:
Locations of Herring Spawn on Vertical Shoreline Structures within the Spill Zone



LOCATION LABELS AND SCENARIO ASSIGNMENT			
Label	Location	Upper Bound	Lower Bound
Submerged Vegetation (e.g., eelgrass)			
1	Nearshore Richardson Bay	X	X
2	Central Richardson Bay	X	
3	Keil Cove	X	X
Shoreline Rocks and Vegetation			
4	Pt. Diablo	X	
5	Sausalito Waterfront	X	X
6	Belvedere/Bluff Point	X	X
7	Marina Green Yacht Club	X	
8	Gas House Cove	X	
9	Fort Mason	X	X
10	Aquatic Park	X	X
11	"Fuel Dock"	X	X
12	South Beach Rip Rap Wall	X	X

FIGURE 4:
Locations of Herring Spawn on Submerged Vegetation and Shoreline Rocks within the Spill Zone

APPENDIX A: Spawn Estimate and Detailed Results of Exposure Quantification

Location	Spawn Date (approximate)	Spawn Biomass (tons)	Egg (billons)	Upper Bound Impact		Lower Bound Impact	
				% Shallow Exposure	% Deeper Exposure	% Shallow Exposure	% Deeper Exposure
Shoreline Rocks and Vegetation							
Candlestick Point	12/17/2007	49.88	4.70	0	0	0	0
Pt. Diablo	1/15/2008	15.94	1.14	100.0%	0	0	0
South Beach Rip Rap Wall	1/15/2008	52.44	3.76	100.0%	0	100.0%	0
Marina Green Yacht Club	1/16/2008	137.40	9.86	100.0%	0	0	0
Gas House Cove	1/16/2008	288.15	20.68	100.0%	0	0	0
Fort Mason	1/16/2008	759.35	54.49	100.0%	0	100.0%	0
Fuel Dock	1/16/2008	486.41	34.90	100.0%	0	100.0%	0
Aquatic Park	1/17/2008	25.73	1.85	100.0%	0	100.0%	0
Paradise	2/18/2008	879.77	86.58	0	0	0	0
Pt. San Quentin	2/18/2008	3,084.48	303.55	0	0	0	0
Belvedere/Bluff Point	2/19/2008	7.98	0.79	100.0%	0	100.0%	0
Sausalito Waterfront	2/19/2008	55.36	5.45	100.0%	0	100.0%	0
Submerged Vegetation							
Central Richardson Bay[1]	12/3/2007	1.81	0.17	1.8%	82.1%	0	0
Nearshore Richardson Bay	12/3/2007	13.91	1.31	33.4%	24.4%	25.1%	21.2%
Central Richardson Bay[1]	12/26/2007	81.08	7.65	10.3%	79.8%	0	0
Nearshore Richardson Bay	12/26/2007	16.16	1.52	33.4%	24.4%	25.1%	21.2%
Oyster Point	12/31/2007	0.45	0.04	0	0	0	0
Central Richardson Bay	1/11/2008	436.84	26.87	18.6%	74.5%	0	0
Nearshore Richardson Bay	1/11/2008	18.69	1.15	33.4%	24.4%	25.1%	21.2%
Central Richardson Bay	1/17/2008	0.16	0.01	0.3%	56.2%	0	0
Nearshore Richardson Bay	1/17/2008	0.40	0.03	33.4%	24.4%	25.1%	21.2%
Nearshore Richardson Bay	2/4/2008	0.36	0.04	33.4%	24.4%	25.1%	21.2%
Central Richardson Bay	2/4/2008	4.62	0.45	2.1%	92.7%	0	0
Paradise	2/18/2008	115.80	11.40	0	0	0	0

Location	Spawn Date (approximate)	Spawn Biomass (tons)	Egg (billons)	Upper Bound Impact % Shallow Exposure	Upper Bound Impact % Deeper Exposure	Lower Bound Impact % Shallow Exposure	Lower Bound Impact % Deeper Exposure
Keil Cove	2/18/2008	7.32	0.72	40.6%	37.1%	6.8%	66.0%
Central Richardson Bay	2/19/2008	115.45	11.36	17.6%	82.4%	0	0
Nearshore Richardson Bay	2/19/2008	34.82	3.43	33.4%	24.4%	25.1%	21.2%
Point San Quentin[2]	2/19/2008	333.86	32.86	0	0	0	0
Nearshore Richardson Bay	3/9/2008	4.05	0.40	33.4%	24.4%	25.1%	21.2%
Central Richardson Bay	3/9/2008	60.31	5.94	2.8%	92.6%	0	0
Vertical Structures							
Pier 38	1/16/2008	51.71	3.71	46.8%	22.9%	0	0
Ball Park/South Beach Wall	1/16/2008	61.47	4.41	48.3%	23.7%	0	0
Pier 50	1/16/2008	293.92	21.09	48.2%	23.6%	0	0
Waterfront	1/16/2008	68.92	4.95	50.6%	24.8%	0	0
Pier 48	1/16/2008	240.19	17.24	45.4%	22.2%	0	0
South Beach Harbor	1/16/2008	75.91	5.45	46.6%	22.8%	0	0
Pier 40	1/16/2008	63.63	4.57	64.7%	31.7%	0	0
Pier 36	1/16/2008	101.58	7.29	59.8%	29.3%	0	0
Pier 30/32	1/16/2008	221.04	15.86	75.4%	24.6%	0	0
Pier 28	1/16/2008	28.64	2.05	61.7%	30.2%	0	0
Pier 26	1/16/2008	64.39	4.62	51.7%	25.3%	0	0
Marina Green Yacht Club	1/16/2008	77.65	5.57	51.8%	26.0%	0	0
Gas House Cove	1/16/2008	19.26	1.38	100.0%	0	0	0
Fort Mason	1/16/2008	488.93	35.08	42.4%	21.3%	22.0%	19.6%
Municipal Pier	1/16/2008	399.32	28.65	28.6%	14.4%	14.9%	13.2%
Pier 45 Seawall	1/16/2008	153.77	11.03	29.7%	14.9%	15.4%	13.8%
Pier 45	1/16/2008	327.94	23.53	36.9%	18.6%	19.2%	17.1%
"Ferry Pier"	1/16/2008	161.38	11.58	52.4%	26.3%	27.2%	24.3%
SF Waterfront Wall	1/16/2008	11.64	0.84	100.0%	0	61.1%	38.9%
Pier 24	1/16/2008	24.45	1.75	51.7%	25.3%	0	0
Pier 54	1/16/2008	121.11	8.69	70.5%	29.5%	0	0

Location	Spawn Date (approximate)	Spawn Biomass (tons)	Egg (billons)	Upper Bound Impact % Shallow Exposure	Upper Bound Impact % Deeper Exposure	Lower Bound Impact % Shallow Exposure	Lower Bound Impact % Deeper Exposure
"Ruins Pier"	1/16/2008	52.38	3.76	86.2%	13.8%	44.8%	38.9%
"The Ramp"	1/16/2008	4.56	0.33	97.0%	3.0%	0	0
Paradise Cay	2/18/2008	0.13	0.01	0	0	0	0
Paradise Park Fishing Pier	2/18/2008	4.42	0.44	0	0	0	0
Richardson Bay Marina	2/19/2008	1.16	0.11	65.9%	34.0%	0	0
Waldo Point Harbor	2/19/2008	0.50	0.05	100.0%	0	0	0
Clipper Yacht Harbor	2/19/2008	17.05	1.68	59.7%	30.8%	28.1%	28.3%
Arques Ship Yard	2/19/2008	22.90	2.25	71.2%	28.8%	0	0
ACOE dock	2/19/2008	28.25	2.78	48.3%	24.9%	0	0
SeaK Dock	2/19/2008	60.16	5.92	61.9%	31.9%	0	0
Schoonmaker Point Marina	2/19/2008	35.73	3.52	49.0%	25.2%	0	0
Sausalito Yacht Harbor	2/19/2008	36.74	3.62	51.1%	26.4%	0	0
"Dunphy Park" Marinas	2/19/2008	2.34	0.23	60.2%	31.0%	28.3%	28.6%
Marin Rod & Gun Club	2/18/2008	22.97	2.26	0	0	0	0
Total		10,435.14	879.39				

Notes:

[1] Minor correction made to spawn estimate

[2] Location renamed to reflect that egg deposition samples were taken outside of spill area