YOUNG SALMONID OUT-MIGRATION THROUGH SAN FRANCISCO BAY WITH SPECIAL FOCUS ON THEIR PRESENCE AT THE SAN FRANCISCO WATERFRONT

Prepared for

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	analysis of variance
CalFED	a cooperative of researchers from University of California, Davis and NOAA Fisheries
CDFG	California Department of Fish and Game
cm	centimeter
EBMUD	East Bay Municipal Utility District
ESU	evolutionarily significant unit
FL	fork length
g	gram
GLM	general linear model
Ha	hectares
kHz	kilohertz
km	kilometer
km^2	square kilometer
LTMS	Long-Term Management Strategy
m	meter
m^2	square meter
m^3	cubic meter
mm	millimeter
MLLW	mean lower low water
NOAA	National Oceanic and Atmospheric Administration
RMS	root mean square (square root of average squared deviation from zero)
sec	second
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service

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EXECUTIVE SUMMARY

The primary purpose of this report is to evaluate the occurrence of young salmon and steelhead at the San Francisco waterfront, with respect to their larger scale migration patterns through San Francisco Bay. Two sources of data were used: a 30-year set of midwater trawl catch at fixed stations conducted by the California Department of Fish and Game (CDFG), and three years of acoustic tag data from a different set of fixed sites that are part of an ongoing, multi-agency cooperative investigation.

About 83 percent of chinook in the 30-year sample were fall-run fish, with 93 percent of lower bay captures occurring from May through July. Next most abundant were spring-run fish (16 percent); the remaining smolts (about 1 percent) were assigned to winter run (12 fish) and late-fall run (four fish). These three non-fall-run races together were captured mainly in April and May. Trawl caught chinook averaged less than 100 millimeters (mm) in fork length (FL).

Most chinook were captured in San Pablo Bay and the Central Bay, where the catch rate in channels was more than ten-fold greater than that on the shoals. This pattern places the fish in an area of strong tidal currents that favors their exit from the bay. The farthest-south Central Bay station, in channel habitat near San Bruno Shoal, had substantial catches, suggesting that the channel between the San Francisco waterfront and Yerba Buena Island should be visited by numbers of chinook in season.

Trawl catch of steelhead was too small for analysis, although eight of the 11 lower-bay captures were in channel habitat.

Acoustic data were analyzed for three years (2007 to 2009), including 2,360 chinook smolts (650 detected in lower bays), 1,485 steelhead smolts (431 in lower bays), and 171 adult steelhead (61 in lower bays). The vast majority of smolts of both species were hatchery fish that were surgically tagged and released in winter. The seasonality of these tag detections is thus largely artificial; more than half of the lower-bay detections were recorded in January through March. Chinook were larger than the average trawl-caught smolt, at a mean FL of 161 mm. These fish transited the lower bays in an average of 2.3 days. Steelhead smolts,

though larger (with an average FL of 236 mm), transited the bays in an average of 3.7 days. Both species were detected more frequently over deep channel habitat as compared to shoal habitat, but steelhead showed a stronger tendency to wander about on shoals.

Of the fish detected in the lower bays, 7.5 percent of chinook, 13 percent of steelhead smolts, and 18 percent of steelhead kelts (adults) were detected at the San Francisco waterfront. Smolt detection durations at the waterfront averaged less than 5 minutes per "visit." Nearly all the individual detection durations were in a range predicted by a simple model employing tidal current speed, and shape and size of the area of detectability. Steelhead detection durations averaged longer than those of chinook, but there were confounding factors in this comparison, including differences among years and tagging programs by various agencies. Most (more than 74 percent) of the waterfront visits by both species were recorded on instruments mounted at Piers 27 and 30, where depths greater than 18 meters (60 feet) are found nearest to shore. For all but a few fish (1 chinook, 12 steelhead), the results point strongly to the conclusion that salmonid smolts were detected by acoustic instruments as they passed by the waterfront on tidal excursions toward South Bay and back to the Golden Gate, and that these fish normally spend very little or no time within developed port facilities.

1 INTRODUCTION

For several years, automated acoustic monitors have been in place at various sites throughout San Francisco Bay in order to detect the passage of transponders implanted into individuals of several fish species. An array of monitors along the San Francisco waterfront, funded by the Port of San Francisco, detected the passage of chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) among other species. The main purpose of this report is to analyze and interpret these detection data along with other relevant data, and more specifically to place the waterfront detections into the broader context of salmonid migration through the bay. Two sources of data were used: a 30-year set of midwater trawl catch at fixed stations conducted by the California Department of Fish and Game (CDFG), and three years of acoustic tag data from a different set of fixed sites that are part of an ongoing, multi-agency cooperative investigation (Burau et al. 2007; Klimley et al. 2009). These datasets have complementary strengths that provide emerging details about the behavior and movements of out-migrant salmonids through the lower bays of the San Francisco Estuary.

For the purposes of this study, "lower bays" are defined as those areas downstream of the Carquinez Strait (i.e., San Pablo Bay, Central Bay, and South Bay), which are more or less defined by the restrictions near Richmond and San Francisco, ending at the ocean entrance at the Golden Gate (Figure 1). Ambiguities in the definition of South Bay (see NOAA 2007) are discussed in a later section.

The salmonid fishes that pass through San Francisco Bay are all of special interest to resource management agencies due to declines in abundance from historic population levels. These fishes consist at present of four runs (fall, spring, winter, and late fall) of chinook salmon and two "evolutionarily significant units" (ESU; Central Coast and Central Valley ESUs) of steelhead (Lindley et al. 2007; Busby et al. 1996). These fishes are all anadromous, the adults spawning in freshwater streams and the young emigrating to the ocean after varying periods of rearing in fresh water. Although some "ocean-type" chinook leave their natal streams as fry, most salmonids undergo physiological and morphological transformations to a more ocean-adapted form called "smolts" (Healey 1983; Moyle 2002; Miller et al. 2010). Extant chinook runs all spawn more than 50 kilometers (km) upstream of the Golden Gate, either in the Sacramento River and its tributaries, the lower San Joaquin River tributaries or in hatcheries. Most of the steelhead do likewise, but some (considered part of the Central Coast ESU) spawn in smaller tributary streams of the lower bays. Steelhead tend to emigrate at significantly larger size than chinook, making them less vulnerable to sampling gear, with consequently less detailed information on natural occurrence in the lower bays. Unlike chinook, some steelhead survive the ordeal of spawning and live to emigrate to the ocean. These out-migrating adults, termed kelts, formed a fraction of the tagged steelhead samples and were analyzed separately.

The trawl data and acoustic tag data sources cited above, like nearly all fixed-station sampling arrays, have some inherent biases, and neither one is "perfect" for studying migration of young salmonids. The CDFG "Bay Study" is a generalized fish and crustacean monitoring program; the midwater trawl used is not optimized for salmonids and, indeed, catches very few of them compared to the species discussed by Orsi et al. (1999). The trawl catch of chinook is too small for many common statistical purposes, necessitating pooling of data over long time periods; trawl catch of steelhead is almost nil. However, the trawl program is virtually the only source of data on seasonality of occurrence in the lower bays, has a long time series spanning a large range of environmental conditions, and provides coverage of areas not served by the acoustic monitoring arrays. The acoustic data are mainly from hatchery fish released at times chosen by the investigators. These fish are larger on average than those captured by trawls. (Timing of trawl catch is not insulated from human action, as hatchery releases surely influence it.) The acoustic data allow precise estimates of migration speed, as well as detection duration in certain areas of interest. With some limitation, the data allow tracking of individual fish. Whether these surgically manipulated subject fish behave like normal emigrant fish is an open question that is addressed where possible in this report.

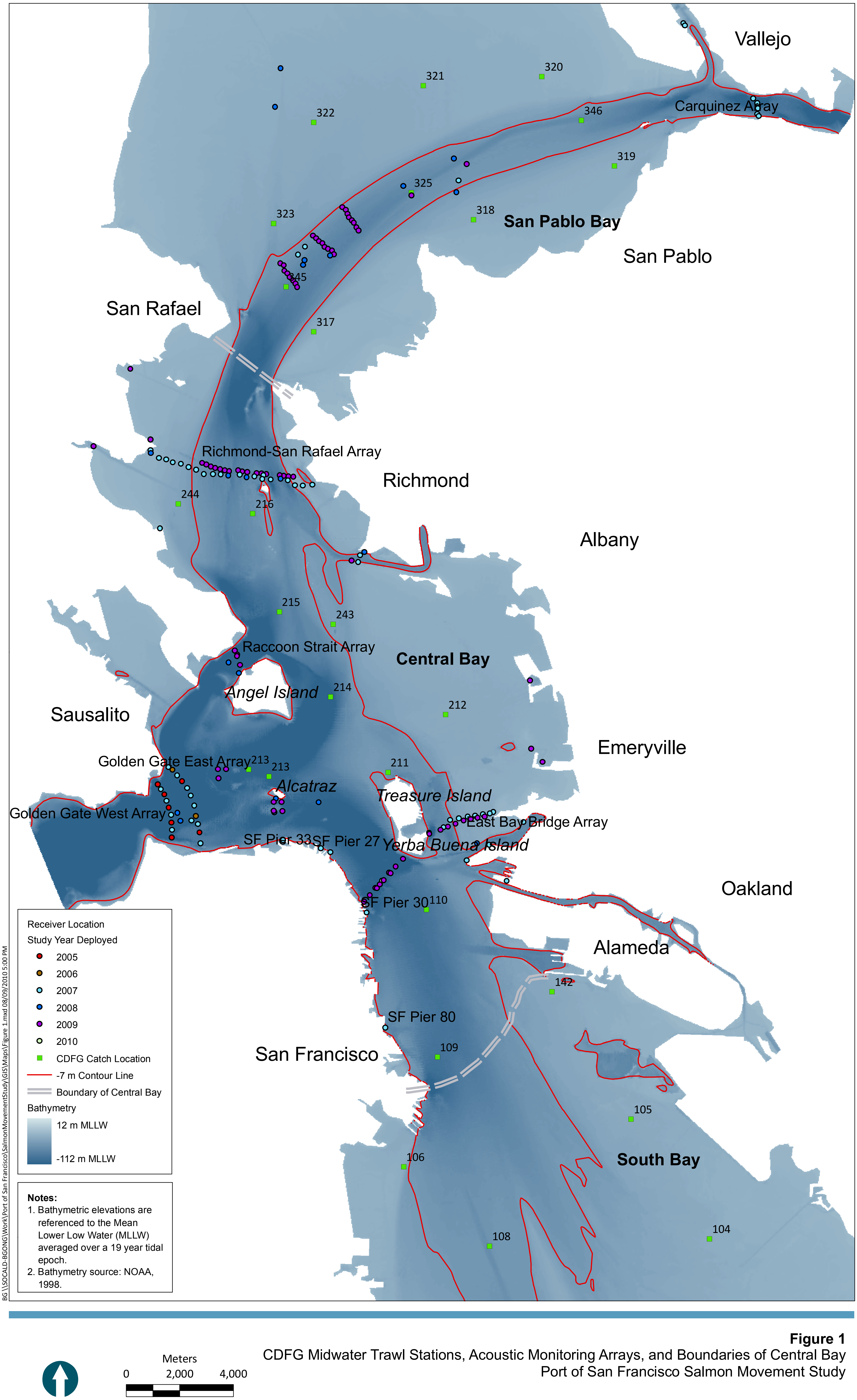


Figure 1
CDFG Midwater Trawl Stations, Acoustic Monitoring Arrays, and Boundaries of Central Bay
Port of San Francisco Salmon Movement Study

2 METHODS

2.1 Trawl Data

Trawl data from the lower bays constituted collections at 30 stations (see Figure 1) taken monthly (with few exceptions) beginning in 1980 or (in six cases) 1988 (see Appendix A). Chinook were tentatively assigned by CDFG to individual runs based on a length-at-date table (the "Delta Model") due to Johnson et al. (1992). This process eliminated chinook greater than 254 millimeters (mm) fork length (FL; less than 1 percent of catch).

The midwater trawl had a mouth opening of 10.7 square meters (m^2) and 13 mm mesh in the cod end. It was towed a standard length of time (12 minutes), stepped obliquely from near the bottom at constant speed. CDFG stations were stratified as to depth, with half the stations in channel habitat and half on shoals (Rosenfield and Baxter 2007). The average volume filtered was about 7,000 cubic meters (m^3), varying (as station average) from about 6,000 to 8,000 m^3 (equivalent to speeds through the water of 0.8 to 1.1 meters per second). However, by keeping effort nearly constant in terms of volume, there is a distinct inshore-offshore bias in these data as to effective area of habitat sampled. That is, in shallower stations, the net spent much more time in a given depth range. The overall range of average depth among stations was 2.5 to 23 meters. The effective area sampled (Smith and Richardson 1977) thus varied from a low average of 278 m^2 at Station 213 (23 meters deep) to 2,718 m^2 at Station 320 (2.5 meters deep). To maintain comparability between shallow and deep areas, the effort for each tow was re-calculated as the volume filtered divided by the depth of bottom measured at the time of sampling, and expressed in m^2 (Smith and Richardson 1977; Smith and Hewitt 1984).

As mentioned in the introduction, salmonid captures were few (median catch = 0). In the 30-year dataset for the lower bays, 1,574 chinook and 11 steelhead smolts were taken. Very little can be done with the steelhead data (see Appendix A, Table A-2). To account for the paucity of chinook captures, the monthly catch at each station was accumulated over all years, divided by the accumulated area sampled at that station, and scaled to average catch per square kilometer (km^2) of effort. It is assumed that abundance is proportional to area-scaled catch, although the possibility exists, for example, that depth-related differences in gear avoidance or perception related to water clarity may cause some residual bias.

2.2 Acoustic Tag Data

2.2.1 Technology

As described in the introduction, acoustic telemetry data of other organizations, whose methods are well described by Klimley et al. (2009), were used in this study. The surgically implanted tags used were small (less than 7 percent of fish mass) acoustic transmitters emitting at a single frequency of 69 kilohertz (kHz). The website of the manufacturer (VEMCO) says the V7 transmitter ranges in mass from 1.4 to 1.8 grams and states the following:

> *Coded tags emit a series of pings called a pulse train which contains ID and error checking information. This allows the user to individually track multiple fish... The time between pulse trains is varied randomly about a nominal point... The off time, or Delay as it is called, is required to ensure that other transmitters have a chance to be detected by the receivers.*

Most of the monitors (VEMCO VR2) were attached either to structures or to moorings; and deployed in what Klimley et al. (2009) termed "curtain arrays," i.e., arrays that span the width of the water body and attempt to provide complete coverage (see Figure 1 for locations). When tag pulses were detected, each monitor recorded the fish ID, with date and time stamp, at fixed locations. These detection records were stored in solid-state circuitry and periodically downloaded and entered into a central database.

CalFED and the U.S. Army Corps of Engineers (USACE) Long-Term Management Strategy (LTMS) studies tagged late-fall-run chinook smolts and juvenile steelhead from the Coleman National Fish Hatchery. Most other agencies also used Coleman Hatchery fish, although the East Bay Municipal Utility District (EBMUD) used steelhead smolts from the Mokelumne Hatchery and also tagged post-spawning adult steelhead (kelts) from the Mokelumne River. LTMS fish were transferred to a facility at the University of California, Davis, where surgeries were performed (USACE 2007). After a short observational period, the fish were released in the wild, upstream of the delta. Some of the fish tagged by other agencies, especially some adult steelhead tagged by EBMUD, were released farther downstream.

2.2.2 Data Structure and Processing

The multi-agency acoustic tag data are maintained by NOAA Fisheries as a *Microsoft Access*® database (hereafter referred to as the CalFED database) consisting of fish identity information (species and source, release date and location, principal investigator, etc.), detector location and maintenance data, and records of fish detections from hundreds of monitors throughout the estuary and nearshore ocean. The tables from the CalFED database that were relevant to this analysis included the master table containing the detections, monitoring locations, fish type, tagging, and release information. Extracted tables were processed in Interactive Data Language for generation of summary tables, statistics, and histograms.

2.2.3 Transit Time

Transit time was defined as the time interval between last detection at the Carquinez array and first detection at the Golden Gate array. A fish was designated as having returned "upstream" if it was detected upstream of the Carquinez Strait after being detected in the lower bays and/or for which the data were consistent with the fish having entered the ocean and spent less than 6 months there before returning to fresh water.

2.2.4 Detection Duration Analysis

Although the main purpose of placing monitors along the San Francisco waterfront was to estimate the amount of time fish are potentially exposed to port maintenance activities, the records of instantaneous detections do not contain information about duration *per se*. To infer duration, it is necessary to make an assumption about where a fish was between detections. While the transmitters emit an acoustic signal every minute or so, many such signals in the vicinity of a monitor go undetected. This conclusion is necessary, because in certain circumstances, e.g., at the "curtain" arrays, improbable movements would otherwise have to be invoked to explain the detection patterns. Still, to define a visit to an array, and to distinguish it from subsequent visits, it is necessary to define a time gap beyond which the fish is deemed to have left the vicinity of the array.

Histograms were developed for delays, or "lags," which were defined as the amount of time between the first detection and each subsequent detection of a fish at a particular station or array of stations. Analysis of lag times at the Richmond-San Rafael Bridge array, which spans Central Bay normal to the main current flow, indicated returns were less frequent after about 5 minutes, although no quantitative argument could be made for any particular time period. Five minutes was chosen as the lag time allowed between detections within a single visit, and a sensitivity analysis was performed to quantify the effect this criterion has on estimates of detection duration.

2.2.5 Statistical Procedures

Confidence limits on means of right-skew data were computed using Equation 1, which assumes a log-normal distribution of sample means (Zweifel and Smith 1981; Jahn and Smith 1987):

$$cl=\mathbf{m}^{*}\exp\{\pm t_{\alpha}\sqrt{[\ln(1 + SE^{2}/\mathbf{m}^{2})]}\} \quad (1)$$

where:

cl	=	confidence limit
m	=	sample mean
t_{α}	=	t statistic for the appropriate percentile and degrees of freedom
SE	=	standard error of mean

All hypothesis testing was done in SYSTAT version 11 or StatXact 4. Parametric tests were performed on log-transformed data to approximate a normal distribution of residuals. In SYSTAT, the general linear model (GLM) module, rather than the ANOVA module, was used for analysis of variance, because the GLM algorithms are more reliable for handling unbalanced designs.

2.3 Tide Data

Data on current speed and direction were based on NOAA models made available through D. Pentcheff at University of South Carolina and obtained from the universities' website (http://tbone.biol.sc.edu/tide). Sites with current "predictions" were selected such that they were as close as possible to the downstream end of the Carquinez Strait (Davis Pt., 38.0500° N, 122.2500° W), northern San Francisco waterfront (Alcatraz south, 37.8167° N, 122.4166°

W), waterfront south (Yerba Buena Island west, 37.8000° N, 122.3833° W), and Golden Gate (San Francisco Bay entrance outside, 37.8105° N, 122.5022° W).

3 RESULTS

3.1 Distribution of Salmonids from CDFG Midwater-Trawl Program

3.1.1 Chinook Smolt Sample Characteristics

According to CDFG's run assignments, about 83 percent of chinook in the 30-year sample were fall-run fish, with 93 percent of lower bay captures occurring from May through July (Figure 2). Next most abundant were spring-run fish (16 percent), although these are believed to be over-estimated because the "Delta model" mis-assigns large fall-run hatchery fish released at Benicia in some years (Hieb 2010); the remaining smolts (about 1 percent) were assigned to winter run (12 fish) and late fall run (four fish). These three non-fall-run races together were captured mainly in April and May. The fall and winter months (September through March) represented only 3.2 percent of all midwater trawl captures of chinook.

The analysis of spatial abundance patterns used catch data scaled to a unit area of trawling effort. To eliminate from this scaling those months that were least productive, only catch and effort data for the months of April through July were used. Mean fork length of chinook captured in this time period was 91 mm, with fall run averaging 89 mm, spring run a bit larger at 98 mm, and the other runs too scarce to make good estimates (Figure 3).

3.1.2 Spatial Pattern of Trawl-Caught Chinook Smolts

As described in the methods section, chinook catches were scaled to effort and expressed as catch rate per km^2 of effort (Table 1). Also tabulated in Table 1 are habitat type (channel and shoal, divided at the 7-meter contour) and embayment (Bay), the stratifying spatial factors in the CDFG study design. Because the shoal stations differed by more than 10-fold in their proximity to deeper water, a measure of distance to water deeper than 7 meters mean lower low water (MLLW) was also added as a covariate. Overall, the combined 30-year catch rate of chinook was over 16 times higher in Central and San Pablo bays than in South Bay and approximately 10 times higher in channels than on the shoals. The abundance is presented in Figure 4, where the sides of the squares representing the station have been scaled proportionally to the catch at that location.

Table 1
CDFG Station Characteristics and Scaled Chinook Catch (1980-2009)

Station	Bay (CDFG)	Bay (This Study)	Habitat	Depth (meter)	Distance to Depths Greater than 7 meters MLLW (meter)	Chinook per Hectare of Effort
101	South	South	Channel	12.7	0	1.0
102	South	South	Shoal	3.5	1,170	0.1
103	South	South	Shoal	3.8	1,024	0.6
104	South	South	Shoal	3.2	4,645	0.1
105	South	South	Shoal	3.5	1,870	0.3
106	South	South	Shoal	3.6	27	0.9
107	South	South	Channel	14.3	0	1.1
108	South	South	Channel	9.9	0	1.1
140	South	South	Channel	14.1	0	0.2
109	Central	Central	Channel	17.9	0	13.6
110	Central	Central	Channel	15.2	0	3.3
142	Central	South	Shoal	4.0	1,829	0.1
211	Central	Central	Channel	7.6	0	3.8
212	Central	Central	Shoal	3.2	1,725	0.9
213	Central	Central	Channel	23.1	0	45.9
214	Central	Central	Channel	16.5	0	17.3
215	Central	Central	Channel	13.8	0	17.3
216	Central	Central	Channel	11.0	0	10.7
243	Central	Central	Shoal	6.6	274	1.8
244	Central	Central	Shoal	4.4	640	2.9
317	San Pablo	San Pablo	Shoal	3.6	50	4.8
318	San Pablo	San Pablo	Shoal	3.5	956	2.9
319	San Pablo	San Pablo	Shoal	3.1	1,120	3.6
320	San Pablo	San Pablo	Shoal	2.9	1,550	1.6
321	San Pablo	San Pablo	Shoal	3.0	2,524	1.4
322	San Pablo	San Pablo	Shoal	3.3	3,045	1.1
323	San Pablo	San Pablo	Shoal	4.7	1,006	1.9
325	San Pablo	San Pablo	Channel	11.8	0	16.9
345	San Pablo	San Pablo	Channel	16.3	0	16.4
346	San Pablo	San Pablo	Channel	11.8	0	33.9

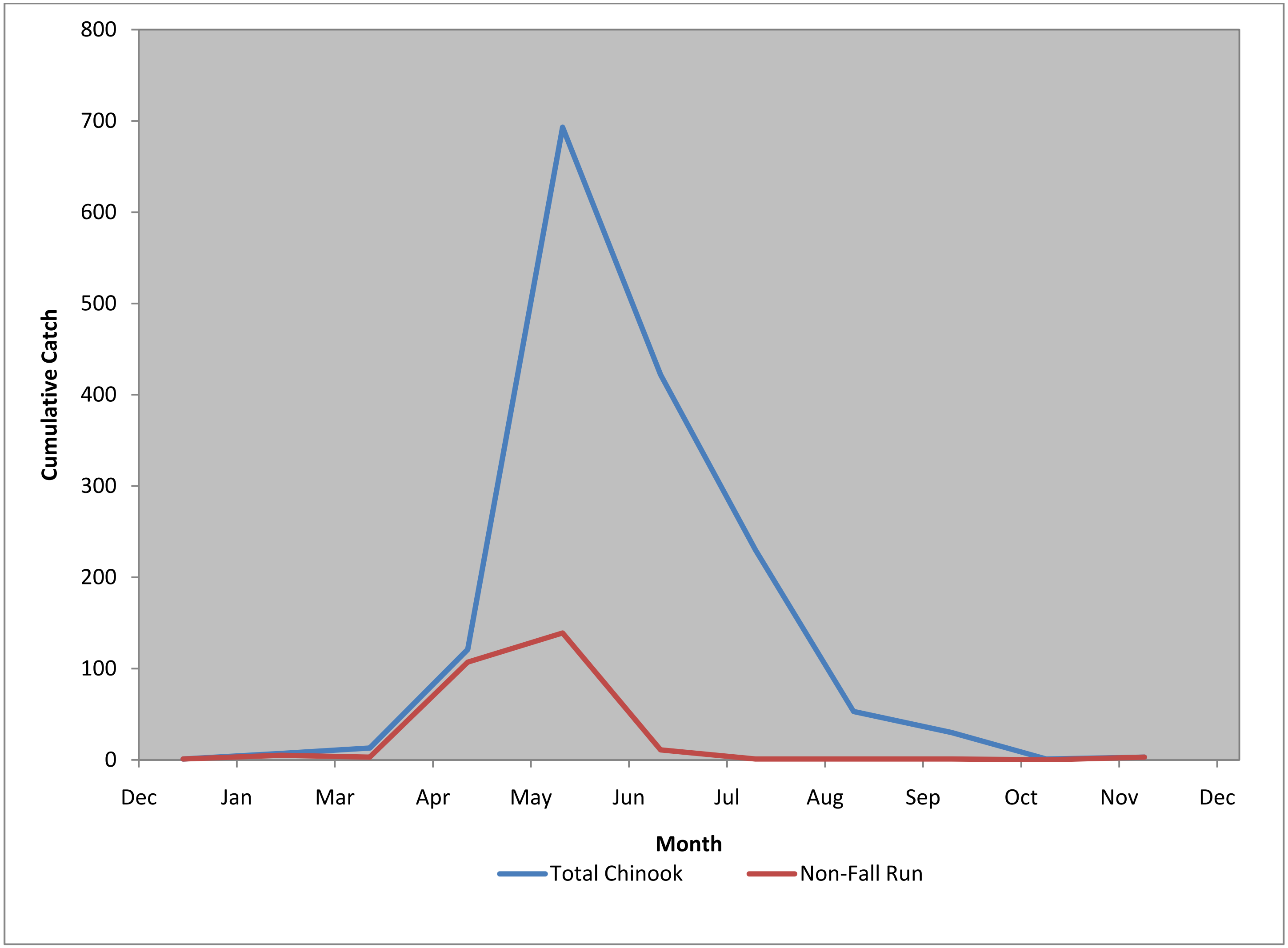
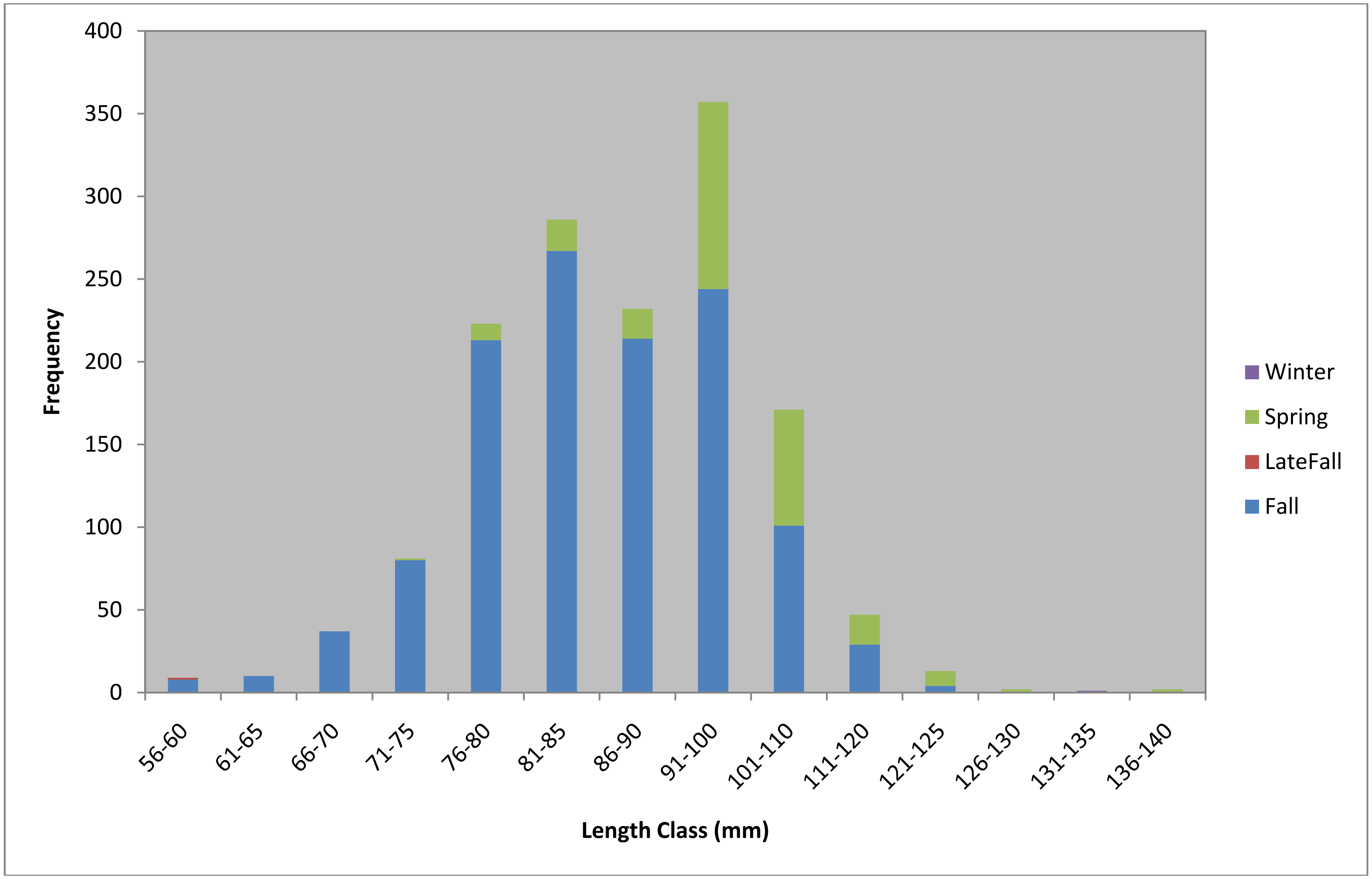
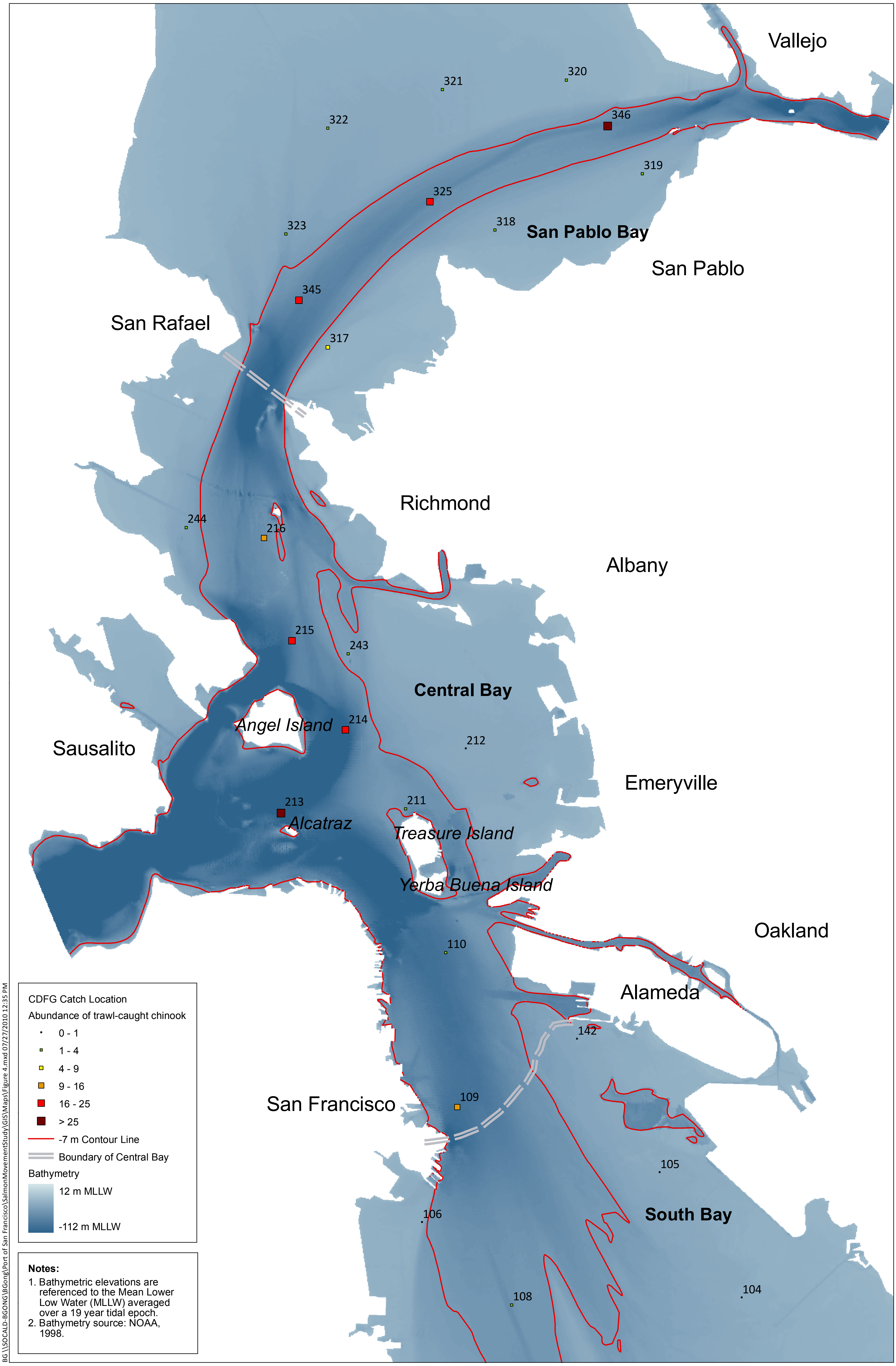


Figure 2
Cumulative Midwater Trawl Catch by Month (1980-2009) in Lower Bay Stations
Port of San Francisco Salmon Movement Study



Notes:
Data collected from 1980 through 2009 during April through July.
A single 44-mm Fall run fish and 197-mm individual, assigned to the Winter run, are not plotted.

Figure 3
Length Frequency Plot (by Run) of Midwater-Trawl-Caught Chinook in Lower Bay Stations
Port of San Francisco Salmon Movement Study



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Meters
0 2,000 4,000

Figure 4
Scaled Catch Rate at CDFG Midwater Trawl Stations (1980-2009)
Port of San Francisco Salmon Movement Study

Largest cumulative catches occurred along the naturally deep channels of the bay, including the catches at Station 109, south of Yerba Buena Island. Thus distributed, chinook smolts are subject to strong tidal action. The relatively high catch rate at Station 109, in contrast to the much lower catches at South Bay stations, is concordant with the view, explained below, that the smolts' passage south of Yerba Buena Island is simply a tidal excursion, followed soon by an exit from the bay on a strong ebb tide. Currents in South Bay are principally tidal, strongly bi-directional and steered by bathymetry (Gartner and Walters 1986). Dissolved and suspended materials (including, for the present purpose, small fish) are considered to oscillate on tidal excursions of ± 10 km (Conomos 1979). Conomos (1979) reported that tidal current speeds on shoals are typically less than half of current speeds in channels (also see Cheng and Gartner 1984). To reflect these circulation patterns, the boundary between South Bay and Central Bay used in this study was assumed to extend to about San Bruno Shoal on the west side of the bay (roughly 10 km south of a line between Treasure Island and the San Francisco waterfront), but only to the shoal south of the former Alameda Naval Station in the east (see Figure 1). This definition places CDFG Station 142 in South Bay rather than in Central Bay.

With this modification to CDFG's stratification scheme, the mean catch rates are presented in Table 2 by embayment and habitat. In agreement with the pattern shown in Figure 4, it appears that the few smolts captured in South Bay were strays that showed little preference for channel habitat. In contrast, in San Pablo and Central bays, the scaled catch rate in the channels was more than 10 times that on the shoals. Using just the San Pablo and Central Bay data, stepwise GLM analysis was performed to evaluate the effects of bay, habitat, distance to the 7-meter contour and various interactions of these effects. A stepwise GLM analysis progressively drops effects and interaction and retains only the most parsimonious model that contributes to explaining the variance of the observed data. Such an analysis found that habitat was the only significant factor, explaining 66 percent of the variance in the catch rate. Because the deep-water connection between Central Bay and South Bay is the narrow passage between Yerba Buena Island and the San Francisco waterfront, this result leads to the expectation that any appropriate sampling device used in that passage would detect these fish, albeit in smaller numbers than occur farther north in Central Bay. This will be discussed further after presentation of the acoustic tag data. This analysis of habitat preference was performed on the entire catch, but much the same results would be expected of the (generally) larger stream-type chinook, because their spatial patterns are highly correlated (fall run versus combined "other" runs; Pearson's r = 0.91).

Table 2
Average Midwater Trawl Catch Rate (Fish per Hectare) of Chinook Smolts in Three Embayments, by Habitat

Bay	Channel	Shoal
San Pablo Bay	22.4	2.5
Central Bay	16.0	1.9
South Bay	0.9	0.6

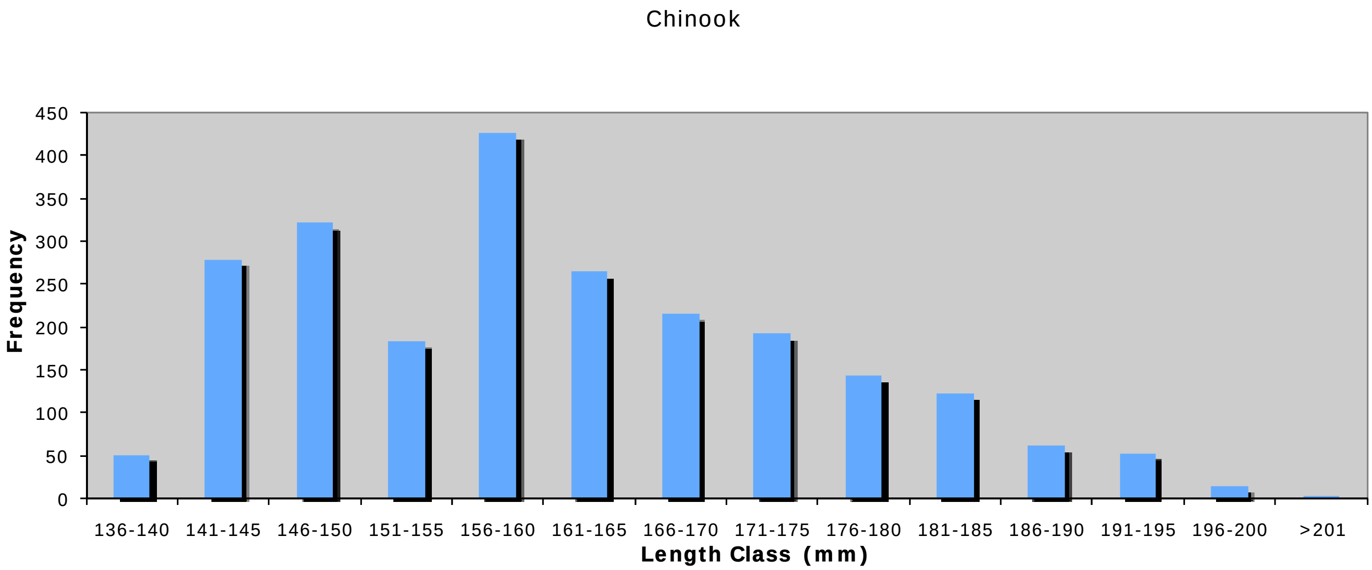
3.1.3 Spatial Pattern of Trawl-Caught Steelhead Smolts

As mentioned above, there is little to analyze in the catch of 11 steelhead smolts in the lower bays (see Appendix A, Table A-2). It is worth mentioning here that only three of these fish were taken in shoal habitat (all at Stations 318 and 319 south of the channel in San Pablo Bay). The three fish taken in Central Bay were all captured at deep-water stations, and the remaining five fish were taken over deep channel habitat in San Pablo Bay.

3.2 Analysis of Acoustic Telemetry Data

3.2.1 Acoustic Sample Size, Fork Length, and Transit Time

Acoustic data were analyzed for three years (2007 to 2009), including 2,360 chinook smolts (650 detected in lower bays), 1,485 steelhead smolts (431 in lower bays), and 171 adult steelhead (61 in lower bays; see Appendix B). Most fish were tagged in winter, and so, unlike the trawl captures, more than 60 percent of the detections in the lower bays were recorded in the first three months of the year. Because of the size requirements for the surgical procedure (tag mass to body mass ratio), the chinook in the acoustic sample are larger than the trawl-caught specimens. Smolt fork lengths (Figure 5) averaged 161 mm for chinook and 236 mm for steelhead. Adult steelhead (kelts) ranged from 320 mm to greater than 600 mm FL, averaging 416 mm.



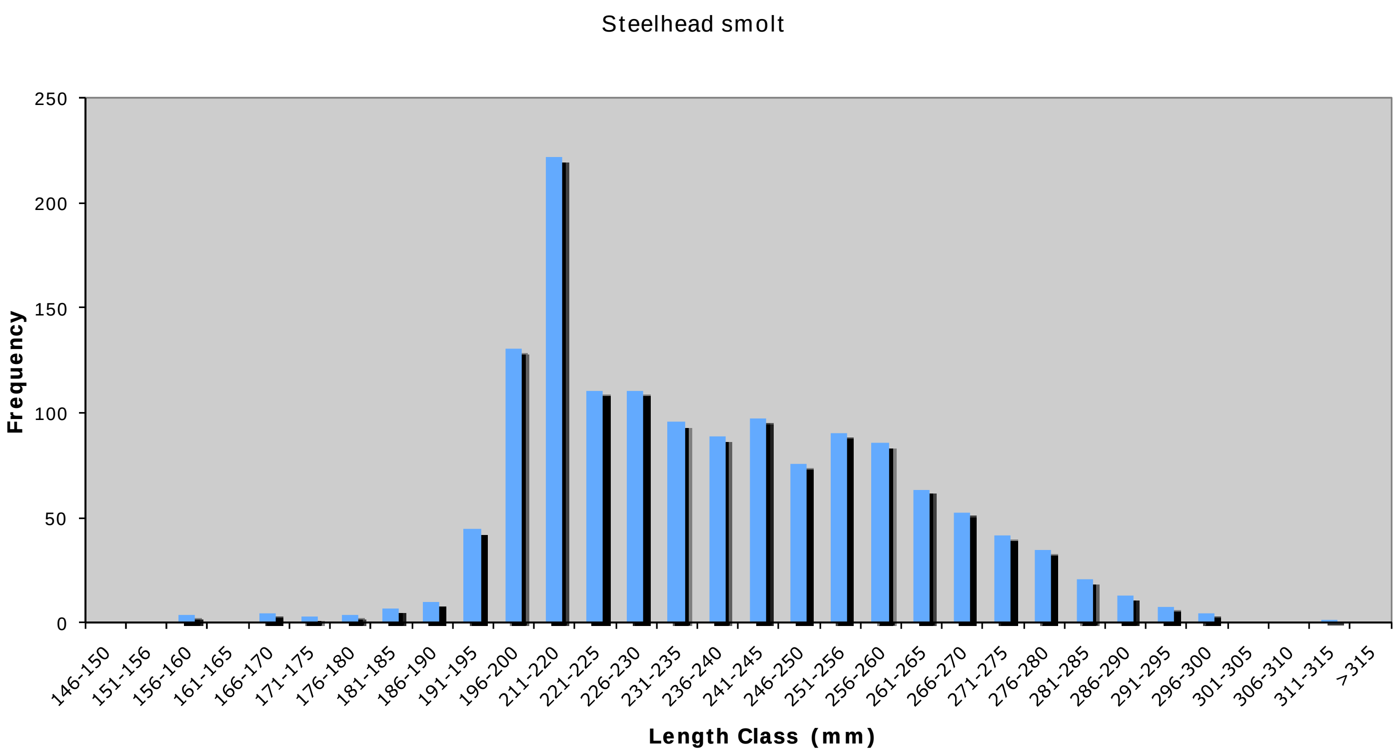


Figure 5
Fork Length Histograms for Chinook and Steelhead Smolts Detected in Lower Bays (2007-2009)
Port of San Francisco Salmon Movement Study

These sizes can be used, for the smolts at least, to anticipate average transit times, i.e., the time between last detection at the Carquinez Strait and first detection at the Golden Gate. If the smolts are envisioned to oscillate with the tidal current, but to sustain a net seaward cruising speed of one body length per second (Webb 1995), then one would expect this distance of 40 km to be transited by chinook in 2.9 days and by steelhead smolts in 1.9 days, based on the body lengths reported above. Actual mean transit times for chinook averaged about 2.3 days (0.6 day faster than expected), with fish from all three main programs averaging within 0.5 day of the overall average. Mean transit time of Steelhead smolts was 3.7 days, with CalFED fish averaging half this time (i.e., about what would be expected based on length), and USACE and EBMUD fish taking about half a day longer than the overall average. Steelhead kelts averaged 1.7 days to transit San Pablo and Central bays, which is 0.6 day longer than would be predicted from the assumption of a cruising speed of one body length per second.

3.2.2 Cross-Channel Distribution of Smolts

As discussed in Section 4.3, surgical and tag effects on fish performance cannot be ignored. One simple test for normal behavior of the fish in the acoustic sample is to inquire whether the detections of the smolts are as strongly concentrated in channel habitat, as were the captures of untagged fish in the CDFG sample. In addition, by analyzing the number of pings per individual fish, other aspects of smolt migration behavior can be examined. For this analysis, the peak period of acoustic tag passage, from January through March, was used. In consideration of the range of the acoustic receivers (imprecisely known, but on the order of 200 meters; USACE 2007), sets of stations on the cross-bay array at the Richmond-San Rafael Bridge were chosen for this analysis such that they were clearly either in channel or shoal habitat, i.e., not within a few hundred meters of the channel edge as represented by the 7-meter contour. These groups of stations (see Figure 6) produced a pattern of acoustic detections (see Appendix C, Table C-1) generally similar to the trawl catch, but with weaker patterns, as described below.

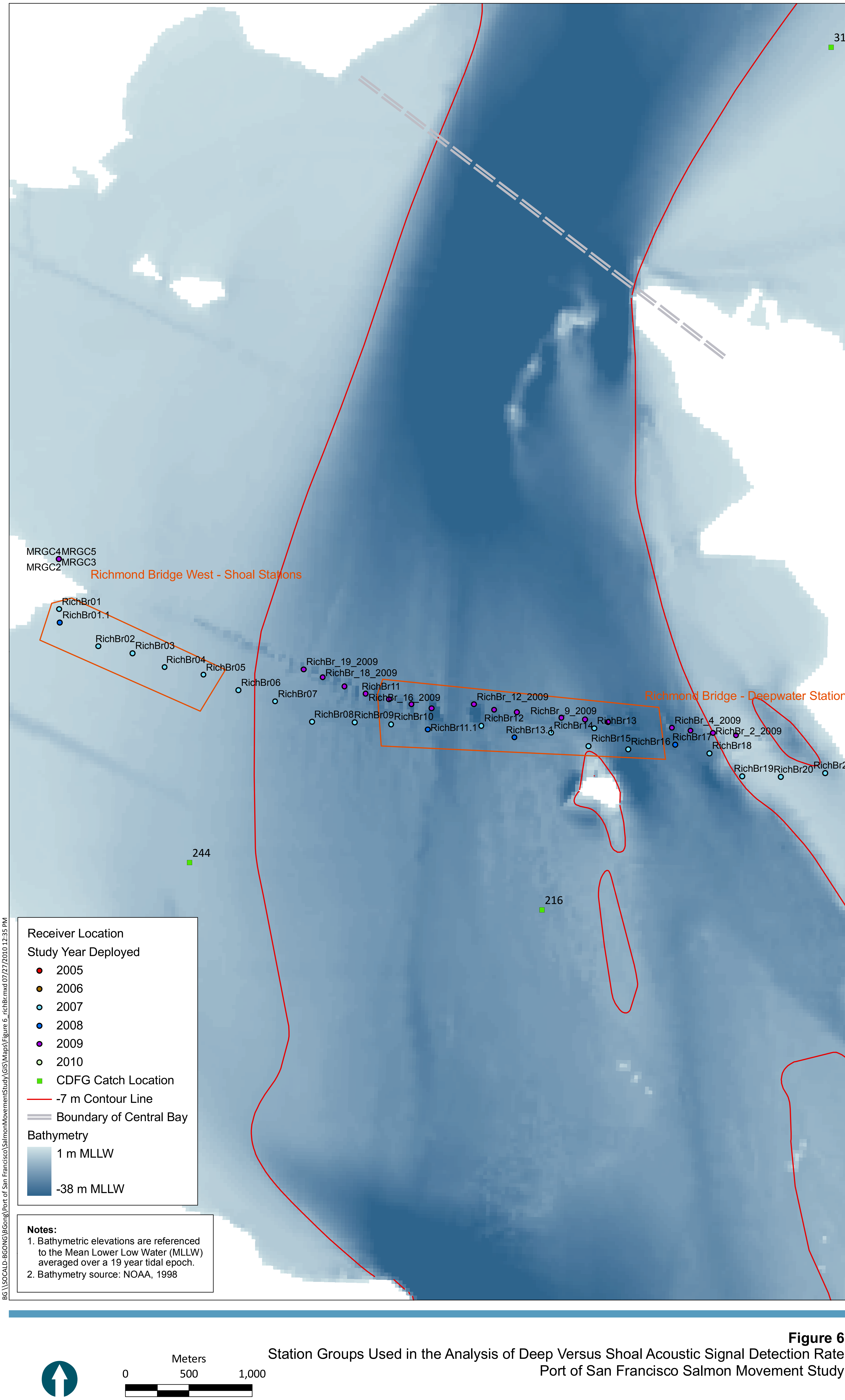


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Figure 6
Station Groups Used in the Analysis of Deep Versus Shoal Acoustic Signal Detection Rate
Port of San Francisco Salmon Movement Study

The station arrangement in 2007 and 2008 allowed a comparison of stations roughly comparable to the CDFG dataset, in that blocks of channel and mid-shoal stations were available as depicted in Figure 6. Complete data are given in Appendix C, and the data are summarized here in Table 3. Before comparing these numbers directly (first two data columns of Table 3), the numbers of fish must be adjusted for the amount of effort, i.e., number of station-days the recorders were active. With this correction, the ratio of the number of fish detected over deep water to the number detected over the shoal ranged from just under two (steelhead in 2007) to five (chinook in 2007), averaging about 2.8 for the two species in these two years. Thus, the tagged chinook venture onto shoals to a greater degree than would be expected based on the trawl data, and tagged steelhead appear roughly similar to tagged chinook in this regard.

In addition to the pathway chosen, one can use this data set to examine whether the fish are behaving similarly in the two habitats. That is, is there a tendency for the fish in either habitat to linger near the receiver (which might occur, say, if the fish preferred one habitat or tended to shelter near the structure supporting the receiver in one habitat more than in the other) or to remain in the habitat and pass by the receiver repeatedly? For this purpose, the average number of pings per fish in either habitat is of interest. The null expectation, i.e., what should occur if there is no effect of habitat, would be that fish in the channel would be recorded less frequently than fish on the shoal, by a factor determined by the difference in the average speed of the currents in the two habitats. In other words, in a faster current, the fish should pass through the detectability range in a shorter period of time. Using a slope and intercept from Cheng and Gartner (1984), the following relationship giving root-mean-square (RMS) speed for San Pablo Bay currents is obtained:

$$\text{RMS current speed} = 20 + 2.71\,z \qquad (2)$$

with speed in centimeters per second (cm/sec) and depth (z) in meters MLLW. With approximate depths of about 4 and 15 meters in the shoal and channel station groups, Equation 2 gives RMS current speeds of 31 and 61 cm/s in shoal and deep habitat, respectively. Thus, the null expectation would be that, on average, fish on the shoal would be detected twice as often as fish in the channel. The "pings per fish" columns in Table 3 do not provide a formal test of this hypothesis, but the results are roughly in line with the null expectation; if anything, chinook in 2007 and 2008 appeared to spend a little less time on the shoals (or more in the channels) than would be expected, and steelhead appeared to linger on the shoals relative to their average ping detection rate in the deep channel. In the deep channel habitat, where the station arrays are comparable among the three years, steelhead ping rates per fish were higher, with no overlap in the average number of pings per fish between the two species (although the rates were similar in 2007). This examination of habitat use may be easier to see in the last column of Table 3, which reports the ratio of pings per fish in shoal habitat to that in deep channel habitat (with a null expectation of two).

In 2009, the mid-shoal block of stations was not sampled, but instead a group of stations very near shore (MRGC1-5; Figure 6) was deployed. Few fish of either species were detected at these nearshore stations, resulting in much higher ratios (13.5 and 8.5) of deep to shoal chinook and steelhead smolts (see Table 3). This shore-based array is outside the range of depths over which the coefficients for Equation 2 were determined, but one would expect the currents to be much slower than in the channel (Conomos 1979). Therefore, the relatively low numbers of pings per fish probably indicate that the fish did not tend to venture very close to the receivers. That is, the detection zones for these shore-based receivers can be thought of as half-circles, wide at the shoreline but getting narrow near the offshore limit of tag detectability; fish passing at a distance from shore near the detection limit would thus be within the detection zone for a short time.

Finally, the greater tendency of steelhead to enter shoal habitat, along with this species' greater number of pings per fish in both habitats, is consistent with the transit times reported in the previous section. That is, steelhead, with greater average body length, tended to migrate through San Pablo and Central bays at a slower rate than expected. All this suggests that steelhead explore the bay habitats more than chinook and take about 60 percent longer to reach the ocean. As previously state, the data as compiled in Table 3 do not provide a powerful test for a difference between species. What can be said here is that, for these two independent measures of average migration speed, the dataset shows a difference in ping rate consistent with a difference in transit time.

Table 3
Smolt Tag Detection at Station Groups near Richmond Bridge

Year	Number of Unique Fish		Pings per Fish		Total Active Station-Days		Ratios[a]	
	Deepwater	Shoal	Deepwater	Shoal	Deepwater	Shoal	Deep/Shoal Fish	Shoal/Deep Pings per Fish
Chinook Smolts								
2007	54	9	8.4	6.4	521	431	5.0	0.77
2008	83	24	5.6	9.0	618	455	2.5	1.61
2009	249	10[b]	5.1	7.6[b]	720	389[b]	13.5[b]	1.49[b]
Total or Average	386	43[b]	5.7	8.1[b]	1,859	1,275[b]	6.2[b]	1.44[b]
Steelhead Smolts								
2007	45	20	8.8	19.3	521	431	1.9	2.19
2008	108	29	9.8	28.9	618	455	2.7	2.96
2009	79	5[b]	12.0	8.8[b]	720	389[b]	8.5[b]	0.74[b]
Total or Average	232	54[b]	10.3	23.5[b]	1,859	1,275[b]	2.9[b]	2.27[b]

Notes:
a The ratio (number of fish deep/number of fish shoal) is corrected for the difference in effort (total active station-days) in the two habitats.
b Station arrangement changed in 2009. See text and Appendix C. See Figure 6 for station groups.

3.2.3 Sensitivity of Detectability Duration to Assumptions

As mentioned in Section 2.2.4, the ping rate of the acoustic signals is roughly once per minute, and not all signals are detected. Determinations of detection duration (i.e., the amount of time a fish spent in the vicinity of a station or group of stations) thus depend to some extent on an assumption that must be made about how long a fish should be considered present in the absence of a detection. In the following presentation, this tolerated period of non-detection is called a "lag time." As can be anticipated, longer lag times should result in fewer, longer visits, and *vice versa*. With too short a lag time, some non-detected pings would falsely be considered absences, and the number of return visits would multiply unreasonably. (Without a lag time [zero lag], each single ping would be a new visit of zero duration, which would be absurd.) With too long a lag time, visits to different stations or arrays would begin to overlap, rendering the term "visit" meaningless. What is desired is an optimum lag time that minimizes errors of both kinds and also allows a standard approach to data processing.

Figure 7 shows the lag times recorded between first and subsequent detections of individual tags in a 30-minute interval starting from the first detection at Richmond-San Rafael Bridge stations. These histograms used the deep stations only (see Figure 6). These graphs show a peak within the first minute or so, followed by a tapering off sometime within the first 5 or 10 minutes. Figure 8 presents the lag times at larger time intervals, starting after the first 30 minutes presented in Figure 7 and extending to 13 hours. These histograms show a second peak in frequency of lags centered approximately on the semi-diurnal tidal frequency of about 6 hours, the importance of which is discussed in the following sections.

The sensitivity of the calculated detection durations to the stipulated lag time was analyzed for the visits at the San Francisco waterfront stations by stipulating 3-, 5-, and 10-minute lag times before considering a detection to initiate a new visit to the station (see Table 4). Always, an increase in lag time resulted in fewer visits and fewer visits of zero duration. Only in adult steelhead was the effect approximately linear, with the greater than three-fold difference in lag time generating approximately a three-fold change in average detection duration from 4 to 11 minutes per visit. In chinook smolts, the average detection duration with a 10-minute lag was only about twice that for a 3-minute lag, and for steelhead smolts the effect was intermediate. There is little in the data to help choose among these options, or to pick any other number for a stipulated lag time. Therefore, in the interest of keeping the criterion the same for both species (thus simplifying data processing), and also based on the patterns in Figure 7, 5 minutes was selected as the lag time.

Table 4
Sensitivity of Detection Duration to Lag Time Stipulation at San Francisco Waterfront Stations (2007-2009)

Lag Time (minutes)	Visits to San Francisco Waterfront	Mean Detection Duration (minutes)	Number of Zero-Duration Visits
Chinook			
3	102	2.0	41
5	91	2.8	34
10	80	4.1	24
Steelhead Smolt			
3	173	3.2	73
5	139	4.9	54
10	111	8.3	34
Steelhead Adult			
3	63	4.0	23
5	47	6.7	14
10	33	11.0	8

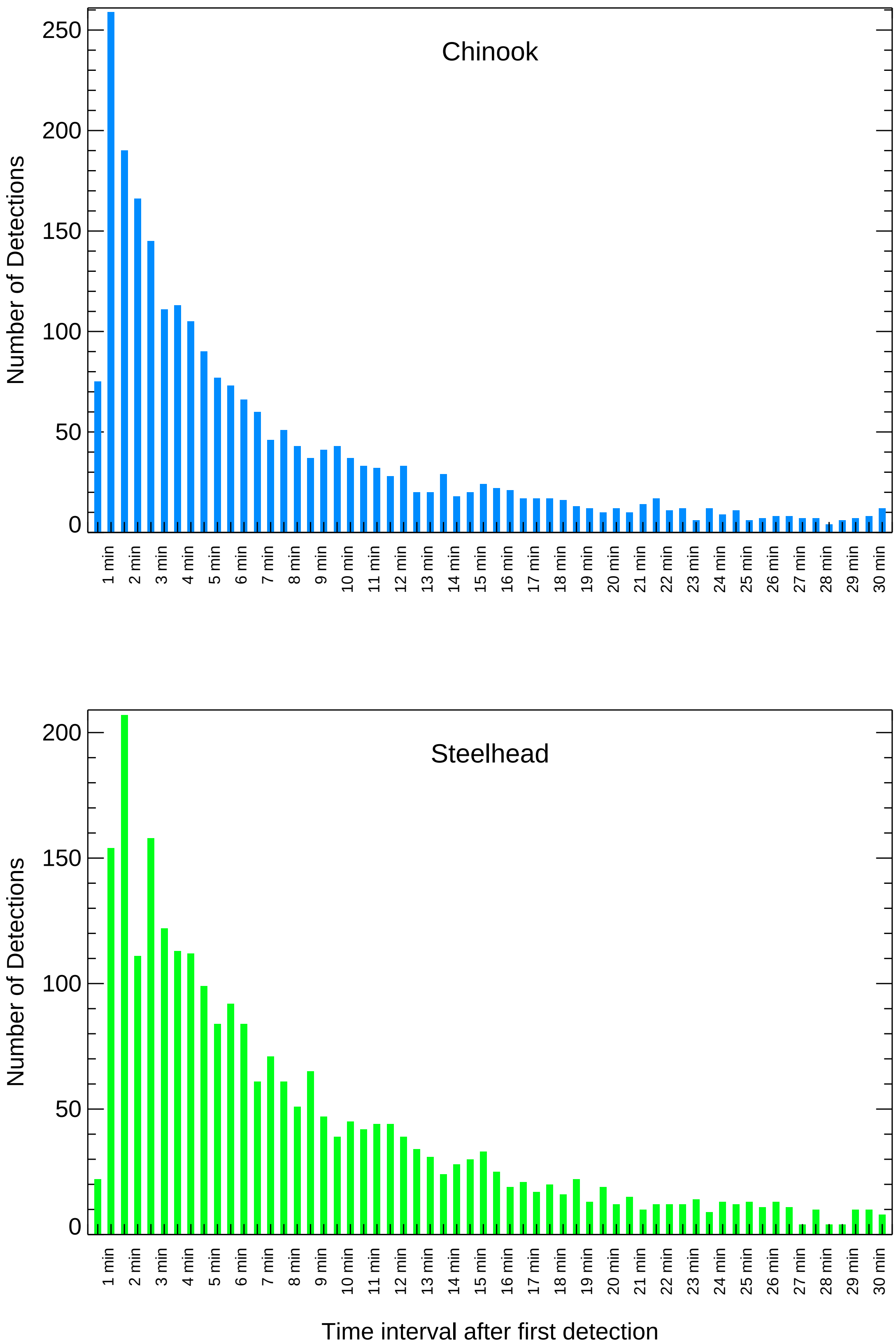

Figure 7

Chinook and Steelhead Lag Time Histograms (0 to 30 Minutes) at the Richmond-San Rafael Array
Port of San Francisco Salmon Movement Study

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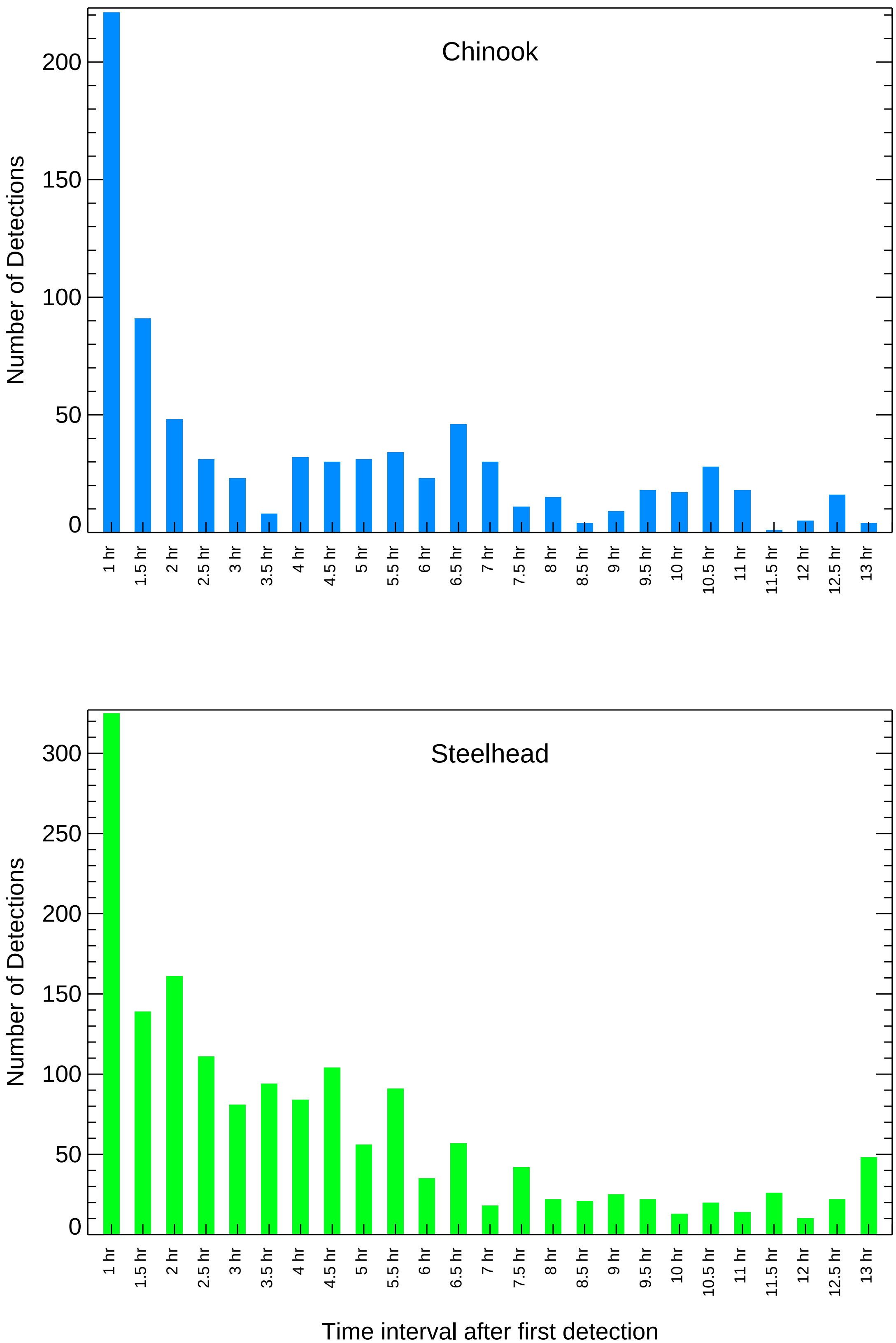


Figure 8

Chinook and Steelhead Lag Time Histograms (30 Minutes to 13 Hours) at the Richmond-San Rafael Array
Port of San Francisco Salmon Movement Study

3.2.4 Relation of Lower-Bay Transit to Tidal Currents

One basic check on the validity, or at least coherence, of the data is to inquire whether the passage of smolts through the lower bays corresponds with hind-cast tidal current data. In Table 5, it can be seen that, overall, a substantial majority of last detections were indeed on ebb tides. (Looking instead at the first detection at the Golden Gate array, which was the criterion for transit time, the result is substantially the same: 67 percent of chinook and 57 percent of steelhead smolts were first detected on ebb tides.) While this result should not be surprising, it is nevertheless a comfort to see this degree of coherence in the data. For instance, if most fish were last detected on flood tides, then there would be much to explain. As it is, it should be noted that some fish were detected at the Golden Gate only on flood tides; this probably means that the fish passed this curtain array undetected (at least once) and were then detected on their way back into the bay on the next tide. Similarly, some fish were detected at the Golden Gate array before they were detected at the Richmond Bridge array. From such observations, it can be concluded that the dataset is not perfect but, more importantly, that the smolts are subject to tidal oscillations as they make their migration.

Table 5

Tidal Relations of Smolt Visits at Two Curtain Arrays, 2007-2009 Study Years

Species of Fish	Number of Fish	Visits per Fish	Percent Last Recorded on Ebb Tide
Carquinez Strait			
Chinook	451	3.7	75%
Steelhead	270	6.2	79%
Golden Gate			
Chinook	268	2.9	74%
Steelhead	186	3.1	62%

The Carquinez and Golden Gate arrays have different geometries, and therefore the number of visits per fish should not be compared between the two arrays in Table 5, except perhaps to compare the efficiencies of the arrays. However, comparing visits per fish between the two species seems a fair thing to do. Steelhead smolts tended to visit the Carquinez array more than half again as often as did chinook, in keeping with the previously noted tendency of steelhead to wander. Apparently, by the time steelhead are ready to go to sea, their wandering tendency is curbed, because at the Golden Gate array they resemble chinook in the number of visits per fish. Alternatively, the lack of a species difference in visits per fish at the Golden Gate array may simply reflect the near-absence of shoals in the area, such that both species are in the same deep-channel habitat, and under the influence of the same very strong current field.

3.2.5 Detection Duration at San Francisco Waterfront Stations

3.2.5.1 A Simple Model of Detectability

Unlike the monitors at the curtain arrays and other open water sites, the monitors at the waterfront can be thought of as shore-based, with an idealized semi-circular detection area having a radius equal to the detection distance. The detection distance is not well-known but is believed to be less than 300 meters (USACE 2007). For a given detection distance, an acoustic tag adrift in a passing current would be detectable for a duration determined by its distance from shore and the speed of the current. For example, if a tag can be detected to a distance of 200 meters from the monitor, a tagged fish passing close to the recorder would be detectable over a distance of about 400 meters. With typical current speeds of 60 to 90 cm/sec in deep water (Conomos 1979), maximum detection durations would be 7 to 11 minutes. Passing the detector at greater distances would shorten the detection durations, out to 200 meters away in the channel, where a fish passing tangent to the detection circle would be recorded either once or not at all.

Assuming that small fish for the most part flow with the current (i.e., ignoring the contribution of cruising speed[1]) and that their distance from shore is random, it is possible to predict a mean detection duration for any given combination of detection distance and current speed. The detectability envelope is a semi-circle of radius equal to the detection distance, as above. The mean path of fish through the semi-circle is a chord of the semi-circle one-half its radius from shore, roughly 1.73 times the detection distance. Because the effect of distance from shore on chord length is non-linear, however, the average detection duration will be that of a fish passing roughly 62 percent of the radius length from the

1 Cruising speed of about one body length per second (see Section 3.2.1) would be roughly 20 to 30 percent of the current velocity.

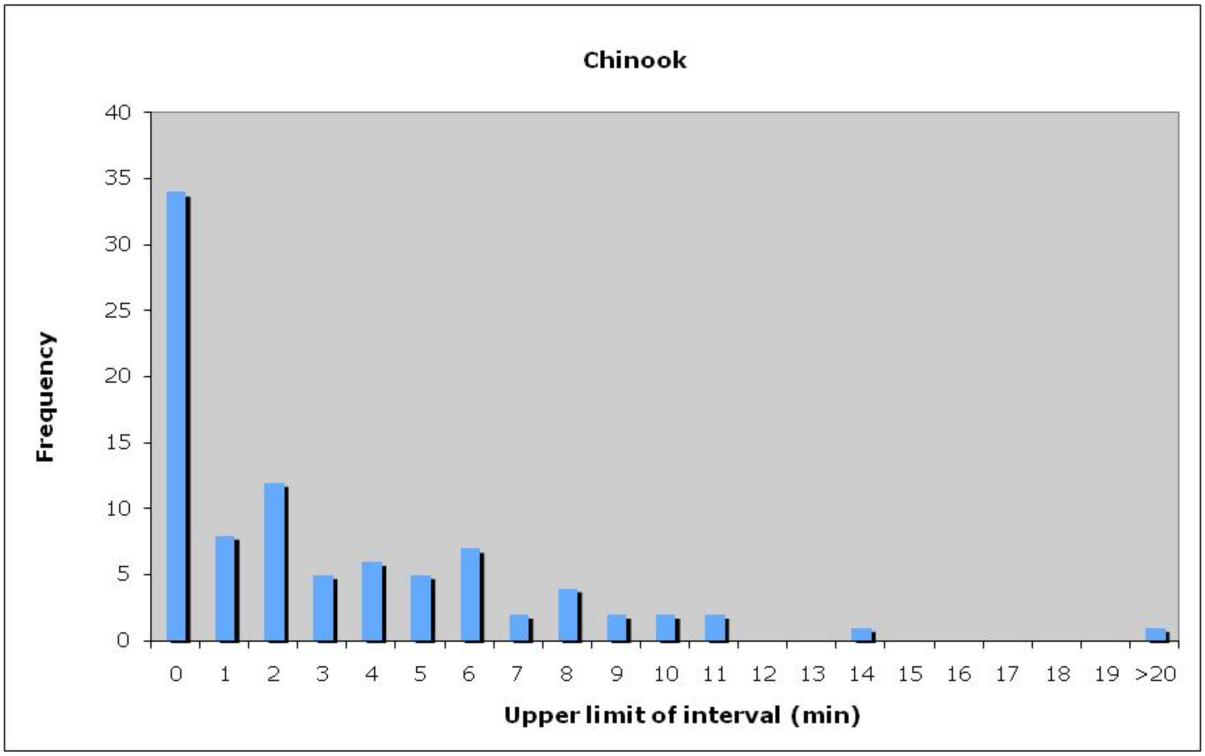
monitor, a distance labeled "weighted mean distance from shoreline" in Table 6. Mean and maximum detection durations are given in Table 6 for reasonable ranges of detection distances and current speeds past the waterfront.

Table 6
Expected Durations of Detectability by a Shoreline Monitor under a Range of Detection Distances and Current Speeds

Detection Distance (meters)	Weighted Mean Distance from Shoreline (meters)	Path Length (meters)	Mean Duration (minutes) at 60 cm/s	Mean Duration (minutes) at 90 cm/s	Maximum Duration (minutes) at 60 cm/s	Maximum Duration (minutes) at 90 cm/s
100	62	157	4.4	2.9	5.6	3.7
150	93	235	6.5	4.4	8.3	5.6
200	124	314	8.7	5.8	11.1	7.4
250	155	392	10.9	7.3	13.9	9.3
300	186	471	13.1	8.7	16.7	11.1

3.2.5.2 Salmonid Detections at San Francisco Waterfront

In all, 49 chinook (7.5 percent of fish detected in the lower bays), 55 steelhead smolts (13 percent), and 11 steelhead adults (18 percent) were detected at monitors placed at one or more locations along the San Francisco waterfront. Although the mean detection durations for the San Francisco waterfront were presented above (see Table 4), the accuracy of these estimates based on overall means bears further analysis. On Figure 9, it can be seen that detection durations of the smolts of both species are right-skew, with a mode at zero minutes, but that the steelhead graph shows a moderate peak in frequency of visits exceeding 17 minutes. (These detection durations are longer than expected from the conceptual model just presented [see Table 6], but not incompatible with it, as slower currents or slack tides could give longer detection durations.) Adult steelhead (kelts, not graphed) displayed several similarly long detection durations, affecting the overall mean. Kelts commonly show signs of post-spawning trauma (e.g., Keefer et al. 2008) and, in any case, were not the subjects of primary interest in this study. Therefore, they were excluded from further analysis.



Notes:
Based on a 5-minute lag time

Figure 9
Detection Duration Histograms for Chinook and Steelhead Smolts at All San Francisco Waterfront Stations
Port of San Francisco Salmon Movement Study

A more detailed analysis was undertaken to understand the cause of longer-duration visits. The mean fork length of the smolts and the release points from the major tagging programs were evaluated (Table 7). Tagged chinook differed somewhat in their fork length and greatly in their point of release. Between 5 and 10 percent of the chinook from the three main programs showed that between 5 and 10 percent of fish returned upstream of Carquinez Strait (the upstream study domain) after being detected in the lower bays. Another 5 to 10 percent were detected at the waterfront stations, and fish from all three programs visited the waterfront roughly two times each, on average.

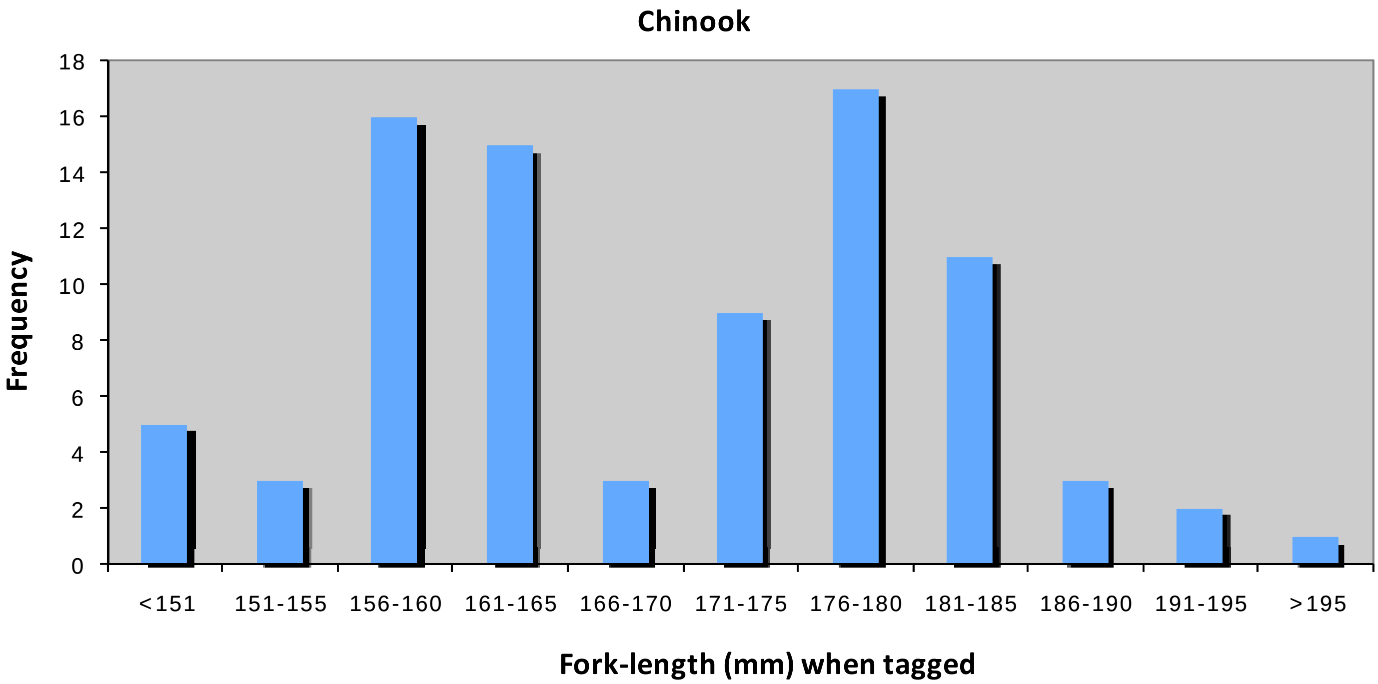
Table 7
Release Data and Frequencies of Chinook and Steelhead Smolt in Four Behavior Categories from Three Tagging Programs

Program	Number Tagged	Average Release Point (km)	Number of Tags Detected in Lower Bays	Mean Fork Length (mm)	Number of Fish		Number of Visits to San Francisco Waterfront	Number of Detection Durations Greater Than 17 Minutes
					Returning Upstream	Detected at San Francisco Waterfront		
Chinook								
CALFED-LFC	731	452	104	161	9	9	18	0
USACE-LFC	585	182	317	173	6	30	52	1
USFWS-PB	1041	175	200	155	14	10	21	0
Steelhead Smolt								
CALFED-STH	751	455	96	224	4	13	22	2
USACE-STH	470	178	271	258	15	28	49	0
EBMUD	263	149	63	234	6	14	68	9

Similar to chinook, the steelhead smolt samples (by tagging program) differed somewhat in fork length and greatly in release point. From 4 to 10 percent of the steelhead detected in the lower bay returned upstream. However, the percentage of lower-bay fish visiting the San Francisco waterfront varied from a little more than 10 percent to more than 20 percent, and visits per fish varied from less than two (CalFED and USACE) to nearly five (EBMUD). Moreover, the EBMUD fish accounted for nine of 11 of the unusually long detection durations shown on Figure 7, despite this program's accounting for only some 15 percent of steelhead smolts detected in the lower bays. Testing for independence of the last three rows and last three columns of Table 7 gives a p-value of 0.0021 (Fisher's exact test), implying that the fish behavior in the bay differs among the three programs. One obvious difference (see Section 2.2.1) is that the EBMUD fish are from the Mokelumne Hatchery, whereas those from the other programs are derived from the Coleman National Fish Hatchery, farther upstream in the Sacramento system. However, the situation is more complex than this, as explained in the following section.

3.2.5.3 General Characteristics of the Acoustic Sample

Tables 8 and 9 give mean detection durations at San Francisco waterfront stations by year for the three main programs for chinook and steelhead, respectively. As can be seen from the numbers of visits listed in Table 7, sample sizes become small at this level of detail. Chinook detection durations (Table 8) varied somewhat from year to year among programs. The larger values for USACE fish in 2007 and 2008 reflect small sample size as shown by the similarity in the overall means of the three programs. This is not the case with steelhead smolts (Table 9); although all three programs had similarly short detection durations in 2009, the detection durations varied by program in other years, and the overall mean for the EBMUD program was nearly twice that for the USACE program, with the mean for the CalFED program being intermediate. Histograms of fork length for smolts visiting the waterfront (Figure 10) have more exaggerated modes than those for lower bay fish in general (see Figure 5). These exaggerated peaks in length frequency are possibly due to smaller sample size, but also are associated with certain unbalanced characteristics of the sample, as shown for steelhead in the next section.



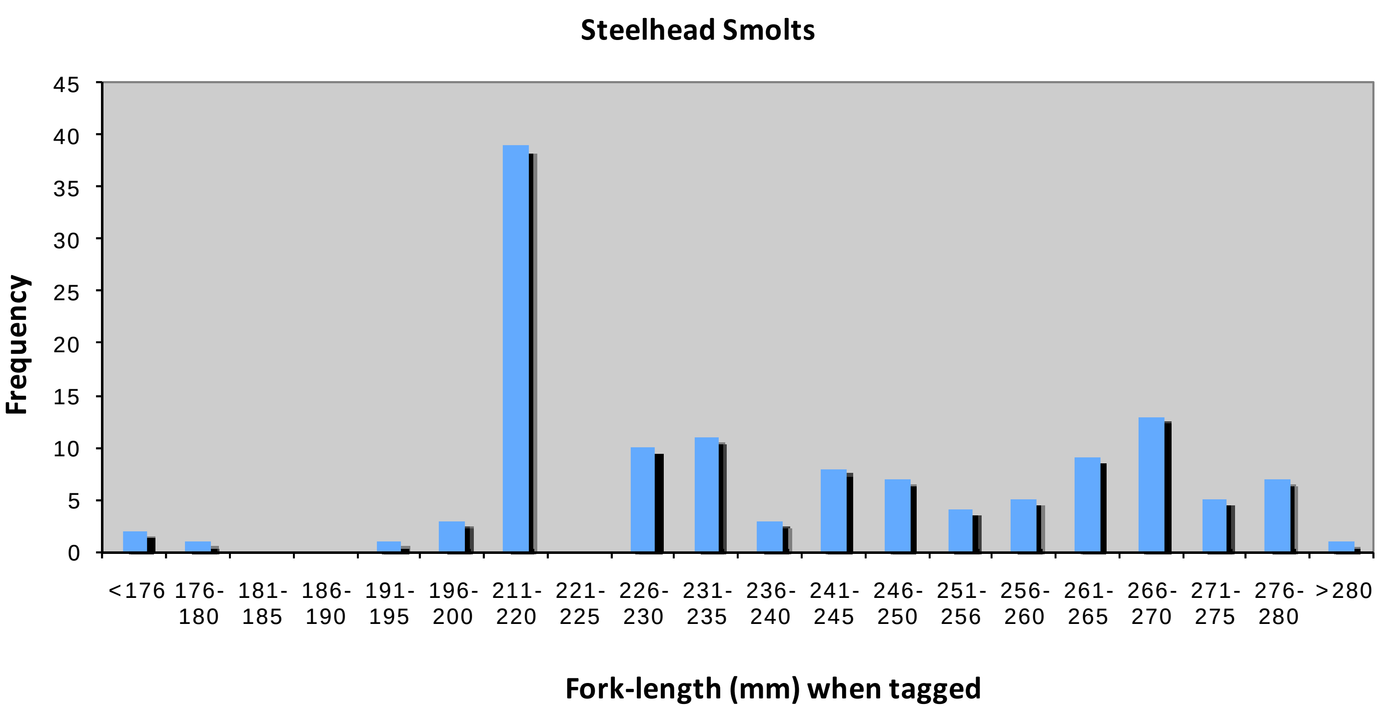


Figure 10

Fork Length Histograms for Chinook and Steelhead Smolts Detected at All San Francisco Waterfont Stations

Port of San Francisco Salmon Movement Study

Table 8
Average Chinook Detection Duration at San Francisco Waterfront Stations by Year and Program

Study Year	Program			
	CALFED-LFC[a]	USACE-LFC[a]	USFWS-PB[a]	Overall Average[a]
2007	–	4.8	2.7	4.0
2008	2.8	7.0	3.8	4.0
2009	3.3	1.7	1.5	1.9
Overall Average	3.0	2.7	2.8	2.8

Notes:
a Average detection durations are in minutes.

Table 9
Average Steelhead Smolt Detection Duration at San Francisco Waterfront Stations by Year and Program

Study Year	Program			
	CALFED-STH[a]	EBMUD[a]	USACE-STH[a]	Overall Average[a]
2007	4.4	8.5	6.7	7.4
2008	10.0	4.6	3.1	4.5
2009	2.2	2.2	1.5	1.8
Overall Average[a]	4.9	6.2	3.2	4.9

Notes:
a Average detection duration is in minutes.

3.2.5.4 Some Peculiarities of the Steelhead Sample

By adding up all the waterfront detection durations for each fish, a random variable is generated that can be related to other information about the individual. Total detection durations for individual fish can in principle be analyzed for the effects of various fixed and random factors. However, attempts to isolate the independent variables that may affect estimates of detection duration were not successful due to missing data, small sample size, and the high degree of multi-colinearity in the dataset. This means, for example, that the release points of the tagged fish are correlated with tagging program, fork length, and, except for one case in steelhead, principal investigator. The exception is the EBMUD program, which had a different principal investigator for steelhead smolts in each study year (see Appendix D). Coincidentally in the case of the EBMUD program, study year and principal investigator are confounded with fork length (Figure 11). Transit time was not calculable for over half the cases and so was omitted. The analysis that had the most degrees of freedom used study year and program as factors and explained 45 percent of the variance in individual fish total detection duration at the waterfront. The significant interaction term "program by year" means that the effect of program was different in different years. This is essentially a restatement of the message of Table 10, which is tentatively interpreted as a sort of learning curve, in which by the third year of the study, program effects vanished and fish were handled similarly among all the programs. Of these 55 total detection durations for steelhead, the 13 longest were from the 2007 and 2008 study years, and the six longest of these were associated with the EBMUD program.

Table 10
Analysis of Variance of a General Linear Model

Source of Variability	Sum of Squares	Number of Degrees of Freedom	Mean-Square	F-Ratio	p-Value
Program	7.649	2	3.825	3.246	0.047
Year	20.263	1	20.263	17.197	<0.001
Program by Year	7.645	2	3.822	3.244	0.048
Error	57.737	49	1.178		

Notes:
The model used is: log(duration) = program + year + program x year
R^2=0.45

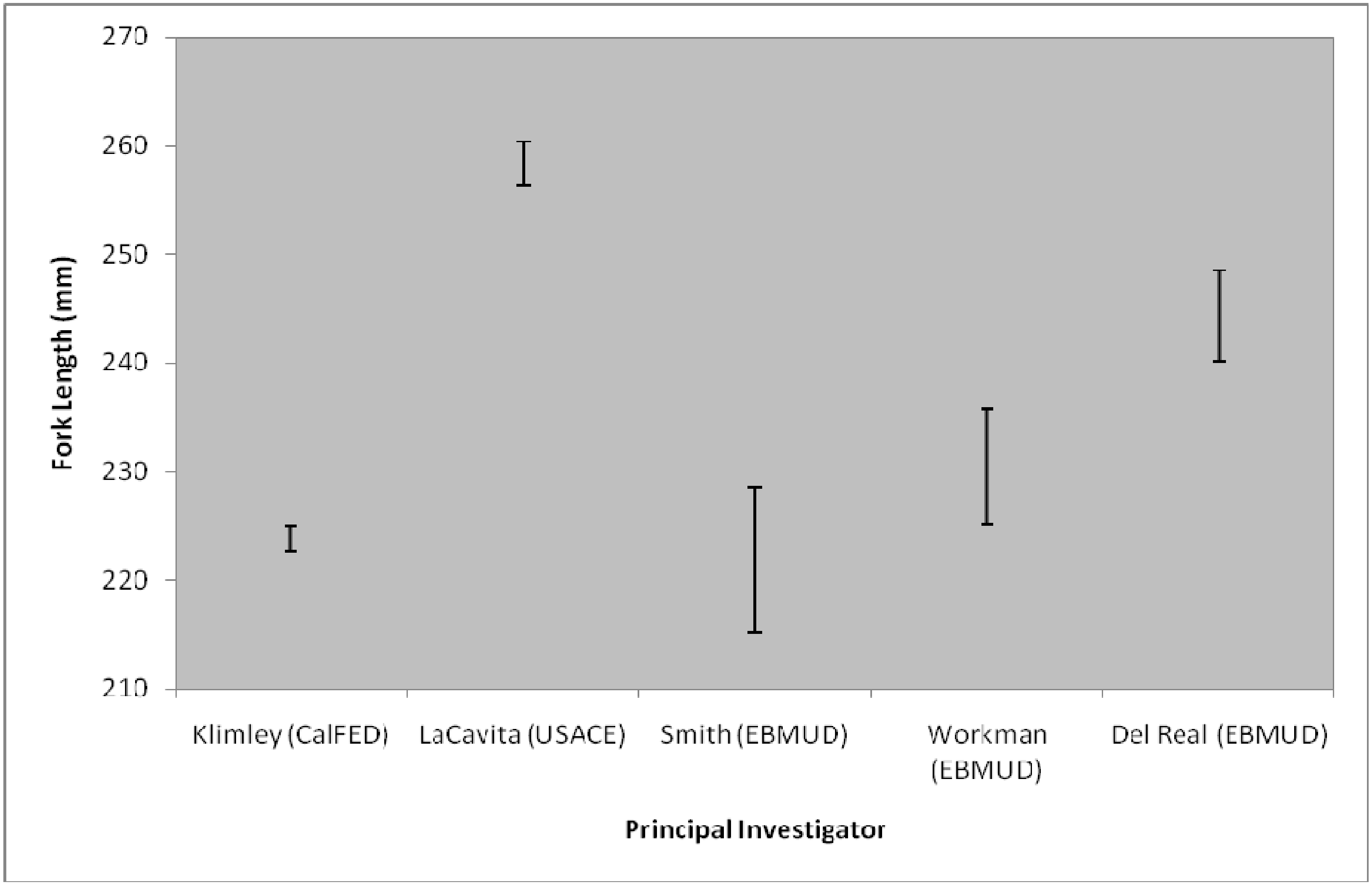


Figure 11
Upper and Lower Confidence Bounds for Mean Steelhead Smolt Fork Length by Principal Investigator
Port of San Francisco Salmon Movement Study

3.2.5.5 Details of Salmonid Detections at San Francisco Waterfront Stations

Among the readers of this report will be those who must make decisions about specific projects in specific areas of the San Francisco waterfront. Despite its limitations, the acoustic dataset is the best available information for predicting fish exposures to projects at the scale of individual piers, berths, and so on. As established by the foregoing analysis, it is generally the case that salmonids do not linger near the piers, i.e., the detection durations are consistent with a model in which the fish drift by in the currents at various distances offshore. However, there is some indication that certain fish, perhaps those suffering effects of the tagging, did remain near some of the monitoring equipment for periods of time longer than expected, and it is worthwhile inquiring whether these events tended to happen in any particular place(s), and whether any other fine-scale spatial patterns may exist in the detection data.

In Table 11, the waterfront fish visits are presented by station and year, with stations arranged in order from north to south. The "effort" at all stations was the same with two exceptions: Pier 27, where the monitor was active for only 68 days in 2007 (versus 190 days at other stations); and Pier 80, where the monitor was active for only 46 days in 2008 (versus 279 days at other stations; see Appendix E). Because of this imbalance, in addition to the demonstration in previous sections that the three years cannot be considered replicates in a statistical sense, no formal analysis of the data represented in Table 11 has been attempted. However, the dearth of fish detections at Pier 45 is immediately obvious, as is the small number of fish detected at Pier 80 at the south end of the array (even in 2007 and 2009, when the effort was standard). Overall, Piers 27 and 30 had the greatest number of visits for both species (greater than 74 percent of all visits), a strong result considering that Pier 27 was under-sampled in 2007. As discussed previously, this is more likely due to proximity to deep water than to any attractiveness of these particular piers to salmonids. Of the five waterfront stations, Piers 27 and 30 are the ones where the wharf face is nearest to naturally deep water, both being within 300 meters of the 18-meter (60-foot) contour.

Pier 45 results are explained by the location of the sensor on the west side of the pier, which is shielded by bulkheads and breakwaters in all directions (Figure 12), except from signals originating within the small harbor formed by these structures. The detection of two steelhead, and no chinook, in this area is perhaps indicative of a greater tendency of steelhead to wander.

Access to Pier 80, south of the Bay Bridge, is via a dredged channel across a natural shoal. The shoal would be expected to deflect most of the tidal flow approximately 1 km offshore of this site, and that is apparently what has occurred for the most part. The longer mean detection durations of a few individuals of both species at this site in 2007 and 2008, discussed previously, may be a result of fish stressed by handling and surgery in those early years of the study.

Table 11

Details of Fish Visits to San Francisco Waterfront Stations, 2007-2009

Station	2007			2008			2009			Total Fish	Total Visits	Grand Mean Detection Duration
	Number of Fish	Number of Visits	Mean Detection Duration	Number of Fish	Number of Visits	Mean Detection Duration	Number of Fish	Number of Visits	Mean Detection Duration			
Chinook Smolts												
Pier 33	1	1	2.8	3	5	1.9	9	15	1.5	13	21	1.7
Pier 27	2	2	4.8	5	10	1.9	14	20	1.9	21	32	2.1
Pier 30	4	5	2.5	9	13	6.3	15	18	2.2	28	36	3.7
Pier 80	1	2	7.5	0	0	N/A	0	0	N/A	1	2	7.5
Total	7[a]	10	4.0	14[a]	28	4.0	28[a]	53	1.9	N/A	91	2.8
Steelhead Smolts												
Pier 45	0	0	0	1	1	0	1	1	4.9	2	2	2.5
Pier 33	3	8	11.5	7	9	0.3	5	5	5.1	15	22	5.5
Pier 27	4	14	7.2	6	15	6.5	10	11	1.8	20	40	5.5
Pier 30	11	18	5.3	11	29	3.7	13	16	0.5	35	63	3.4
Pier 80	3	10	8.0	2	2	22.3	0	0	N/A	5	12	10.4
Total	12[a]	50	7.5	17[a]	56	4.5	26[a]	33	1.8	55[a]	139	4.9

Notes:
a unique fish, not column total

Notes:
The acoustic monitor was attached near the red vessel at lower left.
Image provided by the U.S. Army Corps of Engineers.

Figure 12
Aerial View of Pier 45
Port of San Francisco Salmon Movement Study

4 DISCUSSION

4.1 Migration Patterns

Healey (1991) noted that, apart from differences in timing, "all populations of chinook appear to display similar migratory behavior." This includes self-directed movements that take advantage of water flow toward the sea. Less is known about steelhead, but based on the patterns shown here, they appear to be using similar, generic "strategies" in their out-migration. Out-migrating smolts in San Francisco Bay are clearly under the strong influence of tidal currents. Inspection of detection times shows that a large majority of last detections at the Carquinez array and first detections at the Golden Gate array occurred on ebb tides. Nevertheless, many fish were detected at the San Rafael and San Francisco arrays after first being detected at the Golden Gate. Most (more than 70 percent) of the fish of both species that visited the San Francisco waterfront were first detected there on flood tides, often after first being detected at the Golden Gate array. That is, the fish seem to have been heading for the ocean as expected, got past Angel Island (Klimley et al. 2009), and then were caught on an incoming tide and transported toward South Bay, as described for transport of water properties by Conomos (1979) and Smith (1987).

Both the CDFG and acoustic datasets showed that out-migrating smolts tend to be more abundant in the deep channels of the lower bays than on the shoals. The benefit of this behavior is that the fish are in a higher-velocity, though oscillating, current regime in the deep channel. The currents in the bay are mainly tidal, running parallel to depth contours at speeds correlated with depth (Conomos 1979; Cheng and Gartner 1984; Smith 1987). The fixed arrays of both programs allow only tentative extrapolation of the abundance patterns to unsampled areas. However, where the areas sampled complement one another, such as in the Central-South Bay transition area, a fairly clear picture emerges; the smolts oscillate with the tide, with a net movement toward the Golden Gate. On the west side of Treasure and Yerba Buena islands, the water is deep, the currents are fast, and the smolts are carried on tidal excursions of 10 km or so, typically no farther south than San Bruno Shoal. The absence of acoustic sensors in this southern reach limits this interpretation, but detection durations at the San Francisco waterfront are consistent with this model of an oscillating migration guided by the smolts' tendencies but dominated by tidal currents.

4.2 Considerations for Management

The impetus for the analyses reported here was the finding that some smolts were detected by monitors in place on San Francisco piers. The focus here on larger-scale movements was intended to put the pier observations into perspective. The main findings were that: 1) most salmonid smolts exited the bay without encountering the San Francisco waterfront; 2) the few smolts that were detected by waterfront monitors were for the most part moving past on tidal excursions well offshore; and 3) normally, these fish do not enter developed areas of the waterfront.

These conclusions seem best applied to a determination of whether a proposed maritime activity (e.g., dredging a berth) is likely to create an exposure risk for out-migrating salmonid smolts. The trawl studies help mainly in the general conclusion that these fish tend to migrate in deep water and are therefore less likely to encounter projects in shallow water. The trawl data do indicate a distinct seasonality to the out-migration of chinook, with only some 3 percent of total captures recorded in the fall-winter period, September through March. The trawl data were too sparse to provide information on steelhead seasonality.

The acoustic tag studies reported here were not designed to address the question of seasonality, because the manipulations (surgery and release) imparted a strong seasonal bias to the data. Moreover, the spatial resolution (hundreds of meters) was not well designed for making decisions about projects that typically are proposed at the scale of individual berths or piers. However, the acoustic detection durations at San Francisco waterfront areas were consistent with a model wherein the fish pass by offshore in the tidal currents and thus appear to confirm the expectation that smolts of both species tend to remain in deep water.

In principle, the technology employed by LTMS could be extended to provide answers to basic research questions as well as to give more focus on exposure to maritime activities. Multiple, precisely located sensors with millisecond precision (similar, but not identical, to the VR2 receivers employed at present) could be used to triangulate the three-dimensional positions and movements of tagged fish to within a meter or so. Such an arrangement could be used in the curtain arrays to investigate cruising depth, depth changes, real-time velocities and so on, and it could also be used in port facilities to give much finer resolution on fish interaction with waterfront structures.

Even with the technology currently used, some of the conclusions in the present report could have been more robust with a few changes in the monitor arrays. The absence of sensors in South Bay, the annually changing positions of the monitors along the Richmond Bridge, and spotty (at best) coverage of Racoon Strait are all areas within LTMS control that, had they been more carefully considered, might have led to increased understanding of the migratory pathway. Such knowledge is essential to rational decision-making about population-level exposure to maritime activities.

4.3 Consideration of Tag Effects

The relatively recent technologies that allow the kinds of studies reported here have been proven to provide considerable insight into migratory movements of fish and other animals (Greene et al. 2009; Welch et al. 2007). Even so, all tagging technologies have some uncertainty regarding the effects of handling and the tags themselves on the accuracy of the observations (i.e., the applicability of the behavioral patterns of tagged fish to untagged and wild fish). In the present study, the V7 tag has a mass that ranges possibly from 1.4 to 1.8 grams, which even at the larger size is less than 5 percent of fish body mass in the smallest chinook in the waterfront sample. Nevertheless, this mass must be accelerated every time the fish changes speed or direction. Moreover, the transmitter is a foreign object with a specific gravity of approximately 2, so there is downward pressure on a recently closed wound. Welch et al. (2007) report starting their incision 11 mm forward of the vent, so that the end of the transmitter does not bear upon the sutured incision. USACE (2007), in contrast, made their incisions 3 mm forward of the vent. Studies in several species of salmonids (e.g., Robertson et al. 2003; Welch et al. 2007) indicate extrusion of tags through the body wall or else encapsulation of the tag in new tissue. One study (Hall et al. 2009) reported tag loss through the sutured wound.

The objective of the discussion above is not to criticize any of the investigators or even the technology itself, but simply to point out that tag effects should be expected. Based on a review of literature it became apparent that, at least for the first 60 days or so, fish with implanted telemeters grow more slowly and do not swim quite as fast or avoid predators quite as well as experimental controls, with effects (performance differences) possibly as great as 15 percent (Robertson et al. 2003; Anglea 2004; Welch et al. 2007).[2] With the expectation of effects, this literature needs to be read and cited with a view toward the type-2 error rates in the experiments.[3] Some authors, e.g. Anglea et al. (2004), do report low statistical power to detect the effects they are studying, but such information rarely appears in abstracts or in citations of these papers.

Actual effects may be small, and it is difficult to say how these measures of health and performance might be manifested in the migratory pathway of individuals. As discussed by Chittenden (2009), laboratory experiments cannot be expected to duplicate field conditions, and there will always be some uncertainty about the performance of tagged fish. In this study, it was possible to compare the tagged fish to the CDFG midwater trawl data on capture depth and location, and the results verify—at least qualitatively—that tagged fish and wild fish both migrate along the "spine" of the bay, with little straying onto shoals. There is some indication in the acoustic data, however, that steelhead "wander" more than chinook, including a greater tendency of steelhead to venture into shoal habitat.

In a review of surgical implantation methods for telemetry in fish, Wagner and Cooke (2005) reported that most of the respondents in their survey of researchers in the field believed that the ability and technique of individual surgeons was an important source of potential error that should be accounted for in any study involving multiple investigators. In the San Francisco Bay dataset, because of the relatively small sample, as well as the lack of surgeon identity in the database, a formal covariance analysis of this sort was not feasible. However, factor-effects analysis on the names of the tagging programs and principal investigators found differences due to procedure even at these levels. The long San Francisco waterfront detection durations of certain steelhead smolts, similar to the behavior of spawned-out adult

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2 An exception was the paper by Moore et al. (1990), who used polycarbonate-coated transmitters of approximately 2 percent of fish (Atlantic salmon) body mass and reported no effects on growth, blood composition, or performance. Although their analysis of growth effects was problematic and blood tests lacked power, their test for effects on swimming performance apparently had reasonable power (more than 50 percent), justifying the conclusion that their tags had no apparent effects on this measure of performance.

3 In statistical tests of experimental results, the type-2 error rate is the probability of a false negative, i.e., concluding an effect is absent when in fact it is real. Statistical power is the complement of the type-2 error rate and is increased by such things as controlling outside error sources and increasing the number of independently evaluated experimental subjects.

fish (kelts), were associated with two investigators from one program. Whether these fish should be accepted as normal depends on how one thinks about the procedures involved: anaesthetizing and surgically opening a fish, inserting a foreign object, suturing the animal, and then releasing it after a day of "recovery." A reader who has had surgery might look for assurances as to the expertise of the surgeon performing this work. Other readers might find sufficient assurance in the practice of the interagency database, which simply lists the name and funding source of the principal investigator. In the absence of data, some will wonder whether yearly variability in average detection durations in fish from the other programs may also have been associated with different surgeons, or with surgeons gaining experience over the years. If data on surgeon identity and experience can be assembled from other sources, it would seem prudent to conduct the covariance analysis suggested by Wagner and Cooke (2005).

5 CONCLUSIONS

The results of these essentially observational studies indicate that out-migrating salmonid smolts tend to remain in the deeper channels of the bay, straying only slightly onto shoals and penetrating very little into South Bay, although steelhead appear to "wander" more than chinook. The well-known tidally driven circulation pattern between Central Bay and South Bay entrains some of the fish, which then pass at some variable distance from the San Francisco waterfront. Because the acoustic tags used in the interagency study produce signals that can be detected over distances of several hundred meters by the equipment deployed, the vast majority of detection durations recorded from acoustic-tagged fish can be understood as simply the result of passing at speeds determined principally by the tidally driven current and do not imply any association with waterfront structures. The few (less than 1 percent) surgically tagged fish that were detected for extended periods by a given sensor probably were close to nearshore structures and may have been under the influence of surgical trauma.

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APPENDIX A
CDFG CHINOOK AND STEELHEAD SMOLT CAPTURE DATA

Table A-1
Chinook Smolt Capture Data for Lower Bays

This table is available in the *Microsoft Excel*® spreadsheet attached with the delivery of this document.

Table A-2
Steelhead Smolt Capture Data for Lower San Francisco Bay

Year	Month	Bay[a]	Station	Habitat[b]	Fork Length (mm)	Number Caught
1993	2	2	213	1	190	1
1983	9	2	214	1	151	1
1985	5	2	216	1	285	1
2005	4	2	216	1	189	1
1995	4	3	318	2	199	1
1986	4	3	319	2	375	1
1995	5	3	319	2	204	1
2008	2	3	325	1	204	1
1992	4	3	345	1	221	1
1989	4	3	346	1	281	1
2007	3	3	346	1	166	1

Notes:
Table from California Department of Fish and Game's (CDFG's) San Francisco Bay Study and the Interagency Ecological Program for the San Francisco Estuary
mm = millimeters
MLLW = mean lower low water
a Bay 1 = South Bay, 2 = Central Bay, 3 = San Pablo Bay
b Habitat 1 = channel, 2 = shoal (fewer than 7 meters MLLW)

APPENDIX B
ACOUSTICALLY TAGGED FISH INFORMATION

Table B-1

Salmonid Fish Tagged (Adults Only) or Detected in Lower Bays (2007-2009)

This table is available in the *Microsoft Excel*® spreadsheet attached with the delivery of this document.

APPENDIX C
ACOUSTIC DATA

Table C-1

Acoustic Data for Chinook Smolts, January through March, at Selected Stations Along the Richmond-San Rafael Bridge

This table is available in the *Microsoft Excel®* spreadsheet attached with the delivery of this document.

Table C-2

Acoustic Data for Steelhead Smolts, January through March, at Selected Stations Along the Richmond-San Rafael Bridge

This table is available in the *Microsoft Excel*® spreadsheet attached with the delivery of this document.

APPENDIX D
PROPERTIES OF 55 STEELHEAD SMOLTS DETECTED AT THE SAN FRANCISCO WATERFRONT

Table D-1
Some Properties of the 55 Steelhead Smolts Detected at the San Francisco Waterfront

This table is available in the *Microsoft Excel*® spreadsheet attached with the delivery of this document.

APPENDIX E
DEPLOYMENT DATA FOR SAN FRANCISCO WATERFRONT ACOUSTIC MONITORS

Table E-1

Deployment Data for San Francisco Waterfront Acoustic Monitors

This table is available in the *Microsoft Excel®* spreadsheet attached with the delivery of this document.