Final

An Evaluation of Juvenile Salmonid Routing and Barrier Effectiveness, Predation, and Predatory Fishes at the Head of Old River, 2009–2012



Prepared by:

California Department of Water Resources

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ACRONYMS AND OTHER ABBREVIATIONS

.RAT	raw acoustic tag file
.TAT	track acoustic tag file
°C	degrees Celsius
2D	two-dimensional
3D	three-dimensional
6YSS	Six-Year Steelhead Study
ACV	average channel velocity
AIC_c	Akaike's Information Criterion corrected for small sample sizes
ANOVA	analysis of variance
ATR	acoustic tag receiver
ATTS	Acoustic Tag Tracking System
BAFF	bio-acoustic fish fence
BDCP	Bay Delta Conservation Plan
BL/s	body lengths per second
CCW	counter-clockwise
CDEC	California Data Exchange Center
CFR	Code of Federal Regulations
cfs	cubic feet per second
CIMIS	California Irrigation Management Information System
cm	centimeters
cm/s	centimeters per second
CV	Central Valley
CVP	Central Valley Project
dB	decibels
D_E	deterrence efficiency
Delta	Sacramento–San Joaquin Delta
DGPS	Differential Global Positioning System
DL2D	two-dimensional velocity fields from DL-ADCP data
DL-ADCP	downward-looking acoustic Doppler current profiler
DPS	distinct population segment
DWR	California Department of Water Resources
ESA	federal Endangered Species Act
ESU	evolutionarily significant unit
FL	fork length

ACRONYMS AND OTHER ABBREVIATIONS

FR	*Federal Register*
GIS	geographic information system
GLM	generalized linear model
GPS	global positioning system
HD	Hydrophone
HOR	Head of Old River
HOR study site	Head of Old River, at the divergence of the San Joaquin and Old Rivers
HORB	Head of Old River Barrier
HR	High Residency
HTI	Hydroacoustic Technology Inc.
Hz	Hertz (cycles per second)
ID	identification
IML	Intense Modulated Light
IPLW	inverse path length weighting
J/g	Joules per gram
kg	kilogram
km	kilometer
kHz	kilohertz
LSZ	Low Salinity Zone
m	meter
m/s	meters per second
m^3/s	cubic meters per second
mm	millimeter
MSD	San Joaquin River at Mossdale
n	number of samples
NAVD	North American Vertical Datum of 1988
NFH	National Fish Hatchery
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Association
NTU	nephelometric turbidity units
OCAP	*Long-Term Central Valley Project and State Water Project Operations Criteria and Plan*
O_E	overall efficiency
OH1	Old River at Head
PAR	photosynthetically active radiation

ACRONYMS AND OTHER ABBREVIATIONS

PCC	percent correctly classified
P_E	protection efficiency
$QAIC_c$	the quasi-likelihood equivalent of Akaike's Information Criterion corrected for small sample sizes
RBDD	Red Bluff Diversion Dam
Reclamation	U.S. Bureau of Reclamation
ROC	receiver operating characteristic
RPA	Reasonable and Prudent Alternative
SD	standard deviation
SE	standard error
SFPF	Skinner Delta Fish Protective Facility
SJL	San Joaquin River at Lathrop
SJR	San Joaquin River
SJRRP	San Joaquin River Restoration Program
SL2D	two-dimensional velocity fields from SL-ADCP data
SL-ADCP	side-looking acoustic Doppler current profiler
SWP	State Water Project
TFCF	Tracy Fish Collection Facility
TL	total length
Ua	main channel velocity
U-crit	critical swimming speed
Ue	fish escape velocity
Us	sweeping velocity
USFWS	U.S. Fish and Wildlife Service
UTC	Universal Coordinated Time
UTM	Universal Transverse Mercator
VAMP	Vernalis Adaptive Management Program

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

ES.1.1 BACKGROUND AND PURPOSE

The California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation) manage the State Water Project (SWP) and Central Valley Project (CVP), respectively, and are charged to do so in a manner that maintains the survival of anadromous salmonids subject to the terms of the National Marine Fisheries Service's (NMFS) 2009 Biological Opinion (BO) and 2011 amendments regarding the *Long-Term Central Valley Project and State Water Project Operations Criteria and Plan* (OCAP). Action IV.1.3 of the NMFS's 2009 BO instructs these agencies to "consider engineering solutions to further reduce diversion of emigrating juvenile salmonids to the interior and southern Delta, and reduce exposure to CVP and SWP export facilities." Specifically, one objective of Action IV.1.3 is to "prevent emigrating salmonids from entering channels in the south Delta (e.g., Old River, Turner Cut) that increase entrainment risk to Central Valley steelhead migrating from the San Joaquin River through the Delta."

Returning adult fish of the Distinct Population Segment (DPS) of California Central Valley steelhead (*Oncorhynchus mykiss*) and Central Valley fall-run Chinook salmon (*O. tshawytscha*) utilize the San Joaquin River and its connecting interior and south Sacramento-San Joaquin Delta (Delta) tributaries during their upstream spawning migration, while juveniles use these waterways to move downstream during their emigration to the Pacific Ocean. Increased susceptibility to entrainment and predation at DWR's and Reclamation's water export facilities has been associated with juvenile salmonids moving into Old River in comparison to those juveniles remaining in the mainstem of the San Joaquin River (SJRGA 2011, 2013; Perry et al. 2010; and others). In an effort to reduce the movement of juvenile salmonids into Old River, engineering solutions (e.g., barriers) have been tested at the Head of Old River (HOR) pursuant to Action IV.1.3 of the NMFS BO. While a seasonal barrier in the fall has been part of California's protective fish management measures since 1968 (Hallock et al. 1970), deployment of a springtime barrier is more recent at this location (1992) and uncertainties remain about its performance and effectiveness.

The purpose of this report is to contribute to the required BO Action IV.1.3 by evaluating and summarizing the effects of the non-physical barrier (2009, 2010), no barrier (2011), and physical barrier (2012) treatments and assess their effectiveness at retaining juvenile salmonids in the mainstem San Joaquin River. In addition to supporting Action IV.1.3, this report also provides critical information that improves understanding of how juvenile salmonids and predatory fish behave in the vicinity of the HOR and how effective the tested barriers are in deterring and protecting juvenile salmonids. This information can be used to improve barrier performance. The analyses included in the report focus on the effectiveness of the barrier treatments on juvenile salmonid route fate as influenced by the abiotic factors of ambient light level, water temperature, discharge, and turbidity. Additionally, predatory fish densities and predator fish interactions with the barrier treatments and juvenile salmonids were evaluated. Recommendations for future analyses and studies are identified.

ES.1.2 PHYSICAL PARAMETERS AND BARRIERS EVALUATION

The studies presented in this report were conducted during the spring (late April to May/June) of 2009–2012. San Joaquin River discharge (i.e., flow) varied among years. Discharge was lowest in 2009 and highest in 2011, and in

the intermediate years, 2012 was less than in 2010 (Figure ES-1). The official water year classifications based on May 1 runoff forecasts were described as dry in 2009 and 2012, above normal in 2010, and wet in 2011 (State of California 2013).

In 2009 and 2010, a non-physical barrier (OVIVO™ Bio-Acoustic Fish Fence [BAFF], Fish Guidance Systems Limited, Southampton, United Kingdom) was installed at the HOR. The BAFF comprised an acoustic deterrent stimulus enclosed within a bubble curtain and illuminated by strobe lights. In 2011, high-flow conditions precluded installing a barrier treatment. In 2012, an eight-culvert rock physical barrier was installed.

Discharge and barrier treatment influenced the proportion of San Joaquin River flow that entered Old River. In 2009, low discharge coupled with the resultant relatively strong tidal influence, including many flow reversals in the San Joaquin River and the non-physical barrier treatment caused a high proportion of discharge to enter Old River (0.6 to 0.8 [i.e., 60-80%] of total San Joaquin River flow at the Old River divergence). By contrast, the proportion of discharge entering Old River was lower, about 0.45 to 0.55 in 2010 (non-physical barrier) and 2011 (no barrier). In 2012, discharge proportion was recorded at 0.2 or less, demonstrating the effect of the presence of the rock barrier treatment (Figure ES-1).

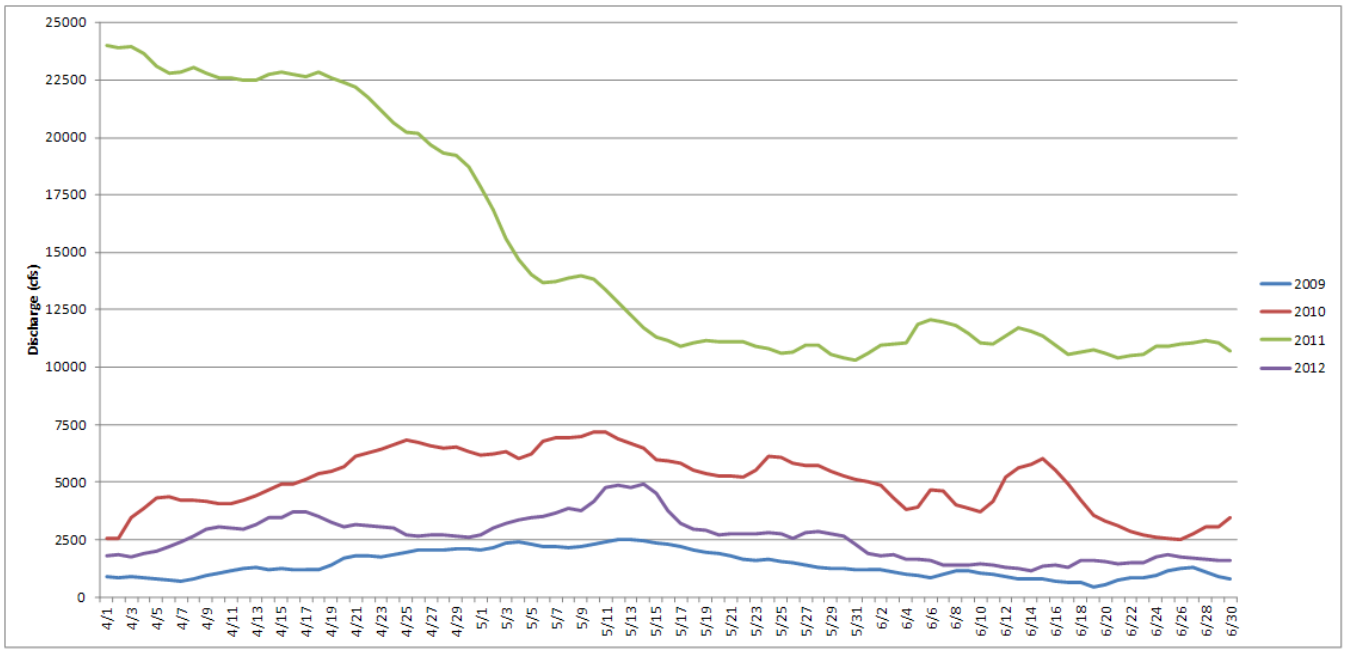


Figure ES-1 Mean Daily River Discharge (cubic feet per second) of the San Joaquin River at Mossdale (MSD), during the study period - April 1 to June 30, 2009–2012

ES.2 OBJECTIVES, METHODS, RESULTS, AND DISCUSSION

The present study included three main objectives, namely to conduct an evaluation at the Head of Old River of:

JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

- Evaluate the effectiveness of different barrier treatments to influence the retention of acoustically tagged (tagged) juvenile Chinook salmon and steelhead in the San Joaquin River, under variable ambient light levels, water temperature, discharge, and turbidity conditions.

PREDATION ON JUVENILE SALMONIDS INCLUDING BARRIER EFFECTS

- Evaluate predation on juvenile salmonids in response to a range of environmental conditions including barrier treatment effects.

BEHAVIOR AND DENSITY CHANGES IN PREDATORY FISHES

- Investigate behavior and density changes in predatory fishes in response to environmental conditions including residence time and assessment of areas occupied.

The following sections briefly summarize the methods used to evaluate the study objectives, the results, and their interpretation.

ES.2.1 EVALUATION OF JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

STUDY FISH

Study fish were obtained from three hatcheries operated by the California Department of Fish and Wildlife. Chinook salmon juveniles were acquired from the Feather and Merced River hatcheries while the steelhead juveniles were acquired from the Mokelumne River Hatchery.

The number of juvenile Chinook salmon surgically implanted with Hydroacoustic Technology, Inc. (HTI; Seattle, Washington) tags was 933 in 2009, 504 in 2010, 1,915 in 2011, and 424 fish in 2012. The size of juvenile Chinook varied by year, but ranged from 80 millimeters (mm) to 140 mm in fork length. Steelhead juveniles implanted with HTI tags were released primarily in 2011 with a total of 2,208 fish which ranged from 149–396 mm fork length. Only 16 steelhead were released in 2012 and these fish ranged in size from 167–269 mm fork length. Juvenile salmonids implanted with VEMCO (Bedford, Nova Scotia, Canada) tags were released in 2012. These fish included 961 juvenile Chinook salmon (100–199 mm total length) and 1,435 juvenile steelhead (115–316 mm total length). Analyses presented in this report focus primarily on juvenile salmonids implanted with HTI tags, unless otherwise specified.

ROUTING AND FATE

The barrier evaluations described in this report were conducted as part of a coordinated suite of studies in the south Delta, which included the Vernalis Adaptive Management Program (VAMP) (SJRGA 1999) and the Six-

Year Steelhead Study (6YSS) (NMFS 2009; SJRGA 2013). This coordinated suite of studies relied on one team (VAMP/6YSS) to conduct the surgical implantation, transport the fish to the release site (i.e., Durham Ferry on the San Joaquin River for all years), handle the fish to minimize effects on behavior, and release the telemetered juveniles according to the schedule.

Each juvenile salmonid entering the HOR study area was categorized based on its apparent fate from observations of two-dimensional tracks detected with a hydrophone array: (1) Released, but never arrived; (2) Remained in San Joaquin River; (3) Entered Old River; (4) Predation; or (5) Unknown. Only fish with fates 2-4 were included in the analyses. Fate was determined qualitatively based on a directed downstream movement for juvenile salmonids. Steelhead did not always move in a downstream direction which made subsequent analyses problematic. In contrast, predatory fish behavior typically included slower movements, looping patterns, and holding the same position.

Each fish was assigned to a sample based on its arrival time into the HOR study area. Samples were created by pooling fish that had arrived at a similar barrier state (BAFF on, BAFF off, no barrier, or rock barrier), ambient light level (< 5.4 lux or ≥ 5.4 lux), and average channel velocity (< 0.61 meter per second [m/s] or ≥ 0.61 m/s).

When barrier treatment status (off/on), ambient light level, or velocity changed, a new sample was created. For testing of BAFF effectiveness in 2009 and 2010, the BAFF was alternated between the "off" and "on" settings so that the BAFF was operational about 50% of the time. This time split in off/on operation allowed about 50% of the tagged juvenile Chinook salmon to experience the BAFF when in operation.

Table ES-1 provides an overview of the fate of tagged juvenile Chinook salmon that entered the HOR study area by year, barrier treatment, and ambient light level. The proportions shown are population proportions (note that population proportions differ from the sample proportions used in hypothesis testing; see Table ES-2). Across all years, the proportion of juveniles that remained in the San Joaquin River (nearly 0.41, i.e., 41%) was similar to the proportion that went down Old River; the remaining 0.19 (19%) were preyed upon. The proportion of juvenile Chinook salmon remaining in the San Joaquin River ranged from 0.09 (BAFF on in the dark, 2009) to 0.84 (rock barrier in the dark, 2012). The proportion of juvenile Chinook salmon entering Old River ranged from 0 (rock barrier, 2012) to 0.78 (BAFF off in the dark, 2009). The proportion of juvenile Chinook salmon that were preyed upon at the HOR study area ranged from 0.03 (no barrier in the dark, 2011) to 0.45 (rock barrier in the light, 2012). A total of 525 tagged juvenile steelhead had their fates determined in 2011–2012, although only five of these fish entered the study area in 2012. Of the 520 juvenile steelhead entering the study area in 2011, the grand overall efficiency was 38.3%, 199 remained in the San Joaquin River, 196 (37.7%) entered Old River, and 125 (24.0%) were preyed upon. There was little difference in routing or predation between light and dark conditions for juvenile steelhead.

Several primary objectives and hypotheses were associated with the evaluation of juvenile salmonid routing and barrier effectiveness (Table ES-2). The evaluation judged efficiency, defining "more efficient" as greater use by juveniles of the San Joaquin River route (over that of Old River) to leave the HOR study area. This definition reflects the general view that survival is lower down the Old River route (see review by Hankin et al. 2010). For each sample, three main metrics were calculated:

- *Overall efficiency* (O_E), the number of tags, originally surgically implanted in salmonid juveniles, exiting downstream from the study area via the San Joaquin River, divided by the number of tags entering the study

area from upstream. This metric provided the most comprehensive measure of barrier effectiveness, as it integrated both routing and loss from predation.

- *Protection efficiency* (P_E), the number of juveniles exiting downstream from the study area via the San Joaquin River, divided by the number of juveniles exiting via the San Joaquin River plus the number of individuals exiting via Old River, but considering only those juveniles that were not eaten at the HOR study area. This metric provided a measure of salmonid juvenile routing through the study area, excluding fish that were preyed upon.

Table ES-1
Fate of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River Study Area during 2009–2012

Year/Barrier/Light*	Total No. of Juveniles	San Joaquin River			Old River			Predation		
		Total	Proportion	SE	Total	Proportion	SE	Total	Proportion	SE
2009 BAFF	525	127	0.242	0.019	278	0.530	0.022	120	0.229	0.018
a. Off	292	68	0.233	0.025	176	0.603	0.029	48	0.164	0.022
i. dark	59	10	0.169	0.049	46	0.780	0.054	3	0.051	0.029
ii. light	233	58	0.249	0.028	130	0.558	0.033	45	0.193	0.026
b. On	233	59	0.253	0.028	102	0.438	0.033	72	0.309	0.030
i. dark	45	4	0.089	0.042	35	0.778	0.062	6	0.133	0.051
ii. light	188	55	0.293	0.033	67	0.356	0.035	66	0.351	0.035
2010 BAFF	451	114	0.253	0.020	220	0.488	0.024	117	0.259	0.021
a. Off	219	45	0.205	0.027	129	0.589	0.033	45	0.205	0.027
i. dark	77	25	0.325	0.053	41	0.532	0.057	11	0.143	0.040
ii. light	142	20	0.141	0.029	88	0.620	0.041	34	0.239	0.036
b. On	232	69	0.297	0.030	91	0.392	0.032	72	0.310	0.030
i. dark	60	28	0.467	0.064	28	0.467	0.064	4	0.067	0.032
ii. light	172	41	0.238	0.032	63	0.366	0.037	68	0.395	0.037
2011 No barrier	1,075	551	0.513	0.015	415	0.386	0.015	109	0.101	0.009
a. dark	306	162	0.529	0.029	135	0.441	0.028	9	0.029	0.010
b. light	769	389	0.506	0.018	280	0.364	0.017	100	0.130	0.012
2012 Rock barrier	193	117	0.606	0.035	0	0.000	0.000	76	0.394	0.035
a. dark	38	32	0.842	0.059	0	0.000	0.000	6	0.158	0.059
b. light	155	85	0.548	0.040	0	0.000	0.000	70	0.452	0.040
Total	**2,244**	**909**	**0.405**	**0.010**	**913**	**0.407**	**0.010**	**422**	**0.188**	**0.008**

Notes: BAFF = Bio-Acoustic Fish Fence (Fish Guidance Systems Ltd., Southampton, UK) (non-physical barrier); SE = Standard Error

* Dark < 5.4 lux, light ≥ 5.4 lux

Source: Present study

Table ES-2
Objectives, Hypotheses, and Results Related to Juvenile Salmonid Routing Including Barrier Effects

Year and Treatment	Objective	Hypothesis Number	Hypotheses	Results*
2009 BAFF	Determine whether barrier efficiency (O_E, P_E, and D_E) for juvenile Chinook salmon was improved by BAFF operation	$H1_0$	For juvenile Chinook salmon, barrier efficiency (O_E, P_E, and D_E) with the BAFF on was equal to barrier efficiency with the BAFF off.	O_E: Accept hypothesis (BAFF on [0.209] = BAFF off [0.184]) P_E: Accept hypothesis (BAFF on [0.338] = BAFF off [0.234]) D_E: Reject hypothesis (BAFF on [0.732] > BAFF off [0.311])
2010 BAFF	Determine whether barrier efficiency (O_E, P_E, and D_E) for juvenile Chinook salmon was improved by BAFF operation	$H2_0$	For juvenile Chinook salmon, barrier efficiency (O_E, P_E, and D_E) with the BAFF on was equal to barrier efficiency with the BAFF off.	O_E: Accept hypothesis (BAFF on [0.355] = BAFF off [0.245]) P_E: Reject hypothesis (BAFF on [0.441] > BAFF off [0.286]) D_E: Reject hypothesis (BAFF on [0.150] > BAFF off [0.012])
	Determine whether BAFF barrier efficiency with the BAFF on changed significantly between years	$H3_0$	For juvenile Chinook salmon with BAFF on, barrier efficiency (O_E, P_E, and D_E) in 2009 was equal to barrier efficiency in 2010.	O_E: Accept hypothesis (2009 [0.209] = 2010 [0.355]) P_E: Accept hypothesis (2009 [0.337] = 2010 [0.441]) D_E: Reject hypothesis (2009 [0.732] > 2010 [0.150])
	Determine whether with the BAFF off, barrier efficiency changed significantly between years	$H4_0$	For juvenile Chinook salmon with BAFF off, barrier efficiency (O_E, P_E, and D_E) in 2009 was equal to barrier efficiency in 2010.	O_E: Accept hypothesis (2009 [0.184] = 2010 [0.245]) P_E: Accept hypothesis (2009 [0.233] = 2010 [0.285]) D_E: Reject hypothesis (2009 [0.312] > 2010 [0.012])
2011 No Barrier	Determine whether and to what extent the BAFF infrastructure affected O_E and P_E when the BAFF was turned off	$H5_0$	For juvenile Chinook salmon, O_E and P_E were equal for 2009 BAFF off, 2010 BAFF off, and 2011 no barrier conditions.	O_E: Reject hypothesis (2011 [0.519] > 2010 [0.245] = 2009 [0.184]) P_E: Reject hypothesis (2011 [0.574] > 2010 [0.286] = 2009 [0.234])
	Determine whether juvenile Chinook salmon and steelhead had the same O_E and P_E through the HOR study area	$H6_0$	O_E and P_E were the same for juvenile Chinook salmon and steelhead.	O_E: Reject hypothesis (Chinook salmon [0.519] > steelhead [0.368]) P_E: Accept hypothesis (Chinook salmon [0.574] = steelhead [0.490])
2012 Rock Barrier	Compare O_E and P_E across treatments to determine whether any barrier was more effective than no barrier and which produced the highest efficiency at retaining juvenile Chinook salmon in the San Joaquin River	$H7_0$	For juvenile Chinook salmon, O_E and P_E were equal for 2009 BAFF on, 2010 BAFF on, 2011 no barrier, and 2012 rock barrier treatments.	O_E: Reject hypothesis (2012 [0.618] = 2011 [0.519] > 2010 [0.355] = 2009 [0.209]) P_E: Reject hypothesis (2012 [1.000] > 2011 [0.574] > 2010 [0.441] = 2009 [0.338])

Table ES-2
Objectives, Hypotheses, and Results Related to Juvenile Salmonid Routing Including Barrier Effects

Year and Treatment	Objective	Hypothesis Number	Hypotheses	Results*

Notes: BAFF = Bio-Acoustic Fish Fence (Fish Guidance Systems Ltd., Southampton, UK) (non-physical barrier); D_E = deterrence efficiency; O_E = overall efficiency; P_E = protection efficiency

* Numbers in brackets indicate sample-based mean efficiency estimates, with statistically significant differences indicated by "<" or ">" and no significant difference indicated by "=."

Source: Present study

- *Deterrence efficiency* (D_E), the number of juveniles approaching the BAFF that were deterred from continuing their approach or were guided along past the end of the BAFF, divided by the total number of juveniles approaching the BAFF. This metric was specific to the BAFF and evaluated its efficacy in producing stimuli noxious to the juvenile salmonids approaching it, as shown by their lack of desire to cross the BAFF.

The analyses of barrier effectiveness found that the BAFF effectively deterred juvenile Chinook salmon from approaching the BAFF in both 2009 and 2010 - that is, D_E was significantly higher with BAFF on than with BAFF off (Table ES-2; Hypotheses $H1_0$ and $H2_0$). D_E was significantly higher in 2009 than 2010 (Table ES-2; Hypothesis $H3_0$), possibly because in 2010 the discharge was higher, a lower proportion of the water column was occupied by the BAFF, and the barrier alignment was different. D_E was also higher in 2009 than 2010 with the BAFF off (Table ES-2; Hypothesis $H4_0$).

Although the BAFF's noxious stimuli were successful in deterring fish from approaching, the BAFF was not efficient in terms of allowing more juvenile Chinook salmon to leave the HOR study area via the San Joaquin River route. There was no significant difference in O_E between BAFF-on and BAFF-off treatments in either 2009 or 2010, and only in 2010 was P_E significantly higher with the BAFF on. These results reflected rates of predation that occurred during BAFF operations (discussed further in Section ES.2.2). There was no significant difference in O_E and P_E between 2009 and 2010, although O_E was close ($P = 0.0563$) to being significantly greater in 2010 (0.36) than in 2009 (0.21). With the BAFF off, O_E and P_E also were not significantly different between 2009 and 2010 (Table ES-2; Hypotheses $H3_0$ and $H4_0$).

The influence of the BAFF's infrastructure alone on survival through the HOR study area was assessed by comparing efficiency (O_E and P_E) with the BAFF off in 2009 and 2010 to efficiency in 2011 (Table ES-2; Hypothesis $H5_0$). Although both O_E and P_E were significantly lower in 2009 and 2010 than in 2011, this comparison was confounded by the very high discharge in 2011, which may have affected the comparison regardless of the presence of a BAFF.

The availability of tracking data for tagged juvenile steelhead moving through the HOR study area in 2011 allowed a comparison of juvenile Chinook salmon and steelhead efficiencies in that year (note that this was not a test of barrier efficiency, but of routing and survival [Table ES-2; Hypothesis $H6_0$]). The routing of juvenile Chinook and steelhead was similar (i.e., no significant difference in P_E), providing evidence of proportional movement that was similar to the proportional split in discharge between the San Joaquin and Old rivers. Juvenile steelhead had significantly lower O_E than the juvenile Chinook salmon, suggesting higher rates of predation. However, this may have been an artifact of juvenile steelhead behavior being similar to predator behavior at times (discussed further in Section ES.2.2).

The analysis of primary importance for addressing management at the HOR study area was the comparison of the efficiencies of different barrier treatments in retaining the juvenile Chinook salmon in the San Joaquin River (Table ES-2; Hypothesis $H7_0$). This analysis revealed no significant difference in O_E between the no barrier and rock barrier treatments in 2011 and 2012, respectively, and that O_E was significantly greater in both of these years than in 2009 and 2010. The fact that all surviving Chinook salmon juveniles remained in the San Joaquin River with the 2012 rock barrier caused the P_E to be significantly higher in 2012 than in all other years, whereas greater discharge in 2011 resulted in significantly greater P_E in that year than in 2009 and 2010.

The primary hypotheses (Table ES-2) were supplemented with supporting hypotheses that evaluated BAFF efficiencies at different levels of light and channel velocity. The light levels considered were dark (< 5.4 lux), and light (≥ 5.4 lux), reflecting the threshold above which light might have affected juvenile Chinook salmon reactions to the BAFF's strobe lights. The channel velocity levels considered were low (≤ 0.61 m/s average channel velocity), and high (> 0.61 m/s average channel velocity), reflecting the sustained swimming speed of small juvenile Chinook salmon, corrected for BAFF angle. The analysis considered these different light levels and channel velocities to account for potential differences in barrier effectiveness because of the visibility of the BAFF and the ability of juvenile salmonids to exhibit swimming avoidance behavior.

Of the three measures of efficiency examined (O_E, P_E, and D_E), only D_E showed a difference between light levels or velocities, and it was significantly higher with the BAFF on in high light conditions (in both 2009 and 2010). This result may reflect a greater ability of juvenile Chinook salmon to orient away from the BAFF's main noxious stimulus (the acoustic deterrent) in high light because of the increased visibility of the BAFF. However, predation increases with higher light level, thus reducing any benefit of the BAFF in providing deterrence (as noted in Section ES.2.2).

ES.2.2 Evaluation of Predation on Juvenile Salmonids Including Barrier Effects

The data on tagged juvenile salmonids described previously were used to address several objectives related to predation in the HOR study area. Those objectives were evaluated by testing univariate sample–based hypotheses in relation to the proportion of salmonids in each sample that were eaten in the study area (Table ES-3; Hypotheses $H8_0$, $H9_0$, and $H10_0$). These analyses generated the following findings:

- The proportion of juvenile Chinook salmon eaten was significantly greater with the BAFF on than with the BAFF off in 2009, but not in 2010 (Table ES-3; Hypothesis $H8_0$);

- In 2011, a significantly greater proportion of juvenile steelhead was eaten than Chinook salmon (Table ES-3; Hypothesis $H9_0$). However, some of the tagged juvenile steelhead categorized as "eaten" may not have been eaten because steelhead sometimes exhibited looping behavior or swam against the flow - behaviors that were used as criteria for determining predation. This would have resulted in an overestimate of the proportion of steelhead eaten; and

- A significantly lower proportion of juvenile Chinook salmon was eaten in 2011 (a high-flow year) than in 2012 (a low-flow year, with the rock barrier in place), whereas the proportion eaten in 2009 and 2010 with the BAFF on was intermediate to, but not statistically different from, the other two years (Table ES-3; Hypothesis $H10_0$).

Table ES-3
Objectives, Hypotheses, and Results Related to Predation on Juvenile Salmonids Including Barrier Effects

Year(s)	Objectives	Hypothesis Number	Hypotheses	Results*
2009	Provide a direct test that the BAFF operation had some influence on proportion eaten.	$H8_0$	The proportion of juvenile Chinook salmon entering the HOR study area that were eaten with the BAFF was on was equal to the proportion eaten when the BAFF was off.	Reject hypothesis: Significantly greater proportion eaten with BAFF on (0.290) than with BAFF off (0.138).
2010	Provide a direct test that the BAFF operation had some influence on proportion eaten.	$H8_0$	The proportion of juvenile Chinook salmon entering the HOR study area that were eaten with the BAFF was on was equal to the proportion eaten when the BAFF was off.	Accept hypothesis: No difference in proportion eaten between BAFF on (0.217) and BAFF off (0.212).
2011	Evaluate the proportion eaten for Chinook salmon and steelhead juveniles in 2011.	$H9_0$	The proportions of juvenile Chinook salmon and steelhead entering the HOR study area that were eaten were equal.	Reject hypothesis: Significantly greater proportion of juvenile steelhead eaten (0.243) than Chinook salmon (0.087).
2009–2012	Show whether there were differences in proportion eaten between treatments.	$H10_0$	The proportions of juvenile Chinook salmon entering the HOR study area that were eaten were equal for 2009-BAFF on, 2010-BAFF on, 2011-no barrier, and 2012-physical rock barrier.	Reject hypothesis: Significantly greater proportion eaten in 2012 (0.354) than in 2011 (0.087), with 2009 (0.290) and 2010 (0.217) intermediate and not significantly different from other years.
2009, 2010, 2012	Evaluate the influence of abiotic and biotic factors, including barrier type/status, on probability of predation of juvenile Chinook salmon.	H11	Probability of predation of juvenile Chinook salmon is negatively related to discharge (shorter travel time/distance at higher discharge), turbidity (lower visual range of predators with greater turbidity), size (larger juveniles less susceptible to predators), and small-fish density (availability of alternative prey for predators). Probability of predation is positively related to water temperature (higher bioenergetic demands of predators with higher temperature) and ambient light level (greater visual range of predators with more light). Probability of predation is unrelated to barrier treatment/status (BAFF on/off, rock barrier).	Hypothesis supported only for ambient light: greater predation probability at higher light level. No support for other hypotheses. Significantly greater probability of predation with BAFF on or rock barrier than with BAFF off. Probability of predation positively related to small-fish density.

Table ES-3
Objectives, Hypotheses, and Results Related to Predation on Juvenile Salmonids Including Barrier Effects

Year(s)	Objectives	Hypothesis Number	Hypotheses	Results*
2011, 2012	Evaluate the influence of abiotic and biotic factors on probability of predation of juvenile Chinook salmon.	H12	Probability of predation of juvenile Chinook salmon is negatively related to discharge, turbidity, juvenile size, and small-fish density. Probability of predation is positively related to water temperature, ambient light level, and density of predatory fish (greater predation pressure with more large fish).	Hypothesis supported only for ambient light and turbidity: greater predation probability at higher light levels and lower turbidity.
2011	Evaluate the influence of abiotic and biotic factors on probability of predation of juvenile steelhead.	H13	Probability of predation of juvenile steelhead is negatively related to discharge, turbidity, size, and small-fish density. Probability of predation is positively related to water temperature, ambient light level, and density of predatory fish (greater predation pressure with more large fish).	Model was a poor fit to the data; results inconclusive.

Notes: BAFF Bio-Acoustic Fish Fence (Fish Guidance Systems Ltd., Southampton, UK) (non-physical barrier); HOR = Head of Old River

* Numbers in parentheses indicate sample-based mean proportion eaten estimates.

Source: Present study

In addition to the univariate sample-based method, generalized linear modeling (GLM) was undertaken. This modeling assessed the potential influence of several environmental variables on the probability of predation of juvenile salmonids at the HOR study area. It also tested the null hypothesis of no difference in predation probability of juvenile Chinook salmon between barrier treatments (BAFF on/BAFF off/rock barrier) for data from 2009, 2010, and 2012 (Table ES-3; Hypothesis H11). The GLM suggested that the probability of predation was significantly greater for the BAFF-on and rock barrier treatments than for the BAFF-off treatment, and that the probability of predation was greater under higher light conditions (presumably because predators could see the juvenile Chinook salmon more easily). This may be the case because juveniles have longer travel distances through the HOR study area as they avoid the noxious stimulus of the BAFF (and may be disoriented by the stimulus) or they are entrained into the eddies created by the rock barrier.

Further analysis was conducted of the data from GLM of juvenile Chinook salmon predation in 2011 and 2012 (Table ES-3; Hypothesis H12) so that the density of large fish from hydroacoustic surveys could be included as a measure of the density of potential predatory fish. This analysis found that the probability of predation was greater at higher light levels and lower turbidities, again suggesting the importance of visibility to predators.

Discharge was not found to be an important predictor of predation probability. To some extent, this may reflect the difficulty in accurately assigning a discharge measurement when conditions are changing rapidly; the higher probability of predation with lower turbidities partly reflects differences in discharge. Relatively low predation at the HOR study area in 2011 may have reflected a downstream shifting of predatory fish (as observed by LeDoux-Bloom [2012] in the broader San Francisco estuary), and predation pressure in response to discharge, because the VAMP study did not find overall through-Delta survival to be greater in 2011 than in other years (SJRGA 2013).

Bioenergetics modeling was conducted to assess potential striped bass predation on juvenile Chinook salmon at the HOR study area. This modeling illustrated that in 2012, the relatively high density of predatory fish (with large fish assumed to be striped bass based on side-looking mobile hydroacoustics), coupled with relatively high water temperature, may have resulted in predation rates similar to those estimated by observing the tagged juvenile Chinook salmon tracks. Lower predatory densities and water temperature estimates in 2011 led to considerably lower estimated predation rates for that year from bioenergetics modeling.

GLM of the probability of predation on juvenile steelhead in 2011 did not yield informative results. To some extent, this may reflect difficulties in assigning steelhead fate, because steelhead movement patterns are less directed than those of Chinook salmon, and steelhead movement patterns may be confused with movement patterns of predatory fishes (Table ES-3; Hypothesis H13).

ES.2.3 Evaluation of Behavior and Density Changes in Predatory Fishes

The behavior of predatory fishes at the HOR study area was studied with more than 80 striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), channel catfish (*Ictalurus punctatus*), and white catfish (*Ameiurus catus*) that were captured by hook and line angling and externally fitted with acoustic tags, primarily in 2011 and 2012. The acoustic detection data from these fish allowed objectives related to residence time and areas occupied by predatory fishes at the HOR study area to be addressed (Table ES-4). In addition, information from mobile hydroacoustic surveys conducted in 2011–2012 and the locations of stationary juvenile salmonids' acoustic tags were used to provide information about the areas occupied by predatory fishes. It was assumed that

the density of fish estimated by hydroacoustic surveys to be at least 30 centimeters (cm) in total length would indicate the density of predatory fishes (recognizing that not all large fish detected would be predatory fishes).

Table ES-4
Objectives Related to Behavior of Predatory Fishes

Years	Objective	Means of Study	Utility to Management
2009–2012	Describe residence time of predatory fishes at the HOR study area.	Tagged predatory fish	Indicates turnover of predatory fish, and therefore allows inference regarding the level of effort required for relocation of predatory fish, for example.
2009–2012	Describe areas (spatial and velocity) occupied by predatory fishes at the HOR study area.	Tagged predatory fish, mobile hydroacoustic surveys, tags from stationary juvenile salmonids (presumably eaten and defecated by predatory fishes)	Indicates where at the HOR study area to focus predator capture efforts for any contemplated relocation efforts, as well as indicating habitat areas that could be manipulated to reduce predator density and predation risk.

Note: HOR = Head of Old River
Source: Present study

The time spent at the HOR study area by tagged predatory fishes varied. Generally, however, channel catfish, white catfish, and largemouth bass spent appreciably longer amounts of time than striped bass (i.e., days or weeks, rather than hours). Most striped bass left the study area in a downstream direction. The significance of the present results for management is that turnover of striped bass generally is appreciable, with most fish spending a limited amount of time at the HOR study area. Thus, efforts to control fish numbers by removal/relocation would require a sustained effort (e.g., daily removal).

The scour hole at the HOR study area was confirmed as an important area for occupancy by predatory fishes. Tagged predatory fishes were found occupying portions of the HOR study area in the San Joaquin River downstream of the Old River divergence, both at the scour hole and in the immediately adjacent areas. Some differences existed in the areas occupied by the different species of tagged predatory fish. For example, striped bass generally were found more often in areas away from shore (although they also occurred near shore), whereas largemouth bass tended to occur more in the nearshore zones.

An analysis of velocities occupied by tagged predatory fishes confirmed the main patterns shown by the spatial analysis of areas occupied. Catfishes and largemouth bass occupied areas with estimated near-surface velocities that were very low compared to all velocities available at the HOR study area. Striped bass differed from the other predatory fishes in occupying a range of velocities, with some individuals having median occupation velocities greater than the median velocities available at the HOR study area; this reflects the species' pelagic nature and occupation of a variety of habitats.

Down-looking mobile hydroacoustic surveys showed an extremely high concentration of large fish (presumably including many predatory fishes, but possibly also including large-bodied nonpredatory fish such as common carp [*Cyprinus carpio*]) in the scour hole; side-looking hydroacoustic surveys similarly showed many large fish in the scour hole, but also showed appreciable numbers in other nearby locations within the study area.

Tags from stationary juvenile salmonids provided a third source of information about areas occupied by predators. The tags also indicated the considerable importance of the scour hole and vicinity because most stationary tags were found there, with very few stationary tags found elsewhere (one tag was also found closely associated with the 2012 rock barrier).

With respect to the occurrence of predatory fish near the installed barriers, tagged largemouth bass that were released downstream of the rock barrier tended to remain at or close to the barrier much of the time, and therefore could have posed a predation threat to any fish passing through the barrier's culverts. A single largemouth bass tagged in 2009 spent an appreciable amount of time (nearly 50% of all detections) within 5 meters of the BAFF (at the upstream end, closest to shore). Little evidence existed of striped bass spending much time close to the BAFF in 2009/2010, although the number of tagged striped bass during these years was very low (n = 4). These findings have important implications for limiting predator abundance at the HOR study area, whether directly (through capture/relocation) or indirectly (through habitat manipulation, such as scour hole filling).

Data from mobile hydroacoustic surveys also were used to address several objectives related to changes in predatory fish density at the HOR study area caused by changes in environmental variables, and to compare density to several reference sites in the San Joaquin River (Table ES-5). GLM suggested that based on both down-looking and side-looking mobile hydroacoustic surveys, the main environmental predictors associated with changes in the density of large fish (greater than 30 cm total length) were same-day discharge and water temperature (Table ES-5; Hypothesis $H14_0$). Density increased as discharge decreased and water temperature increased.

To some extent, the correlation between density of large fish and discharge and water temperature reflected both differences between years and differences within years. The density of large fish was considerably less in 2011 than in 2012; discharge was considerably higher in 2011 than in 2012. The lower density of large fish, presumably including many predatory fish, in 2011 may reflect lower habitat suitability associated with higher water velocities. The 2012 surveys provided a contrast between very low abundance during March, which had low water temperatures (approximately 12–15°C), and higher abundance in May (18–22°C). This suggests seasonal migration to and through the HOR study area by large fish, such as striped bass that spawn in the river during the spring. Although density estimates were quite variable at all the sites, positive correlations in large-fish density existed between the HOR study area and the reference sites in approximately half of the comparisons (Table ES-5; Hypothesis $H15_0$). Large-fish density at the HOR study area was either greater than or not significantly different from large-fish density at the three reference sites (Table ES-5; Hypothesis $H16_0$).

Taken together, these results suggest that wide-ranging factors (e.g., discharge and water temperature) affect fish density over much of the San Joaquin River, and that the HOR study area has a relatively high density of large fishes compared to reference sites. These findings have management implications when prioritizing predator management efforts at the HOR study area and elsewhere in the interior and south Delta, both temporally (within and between years; e.g., there may be more need to capture/relocate predators in warmer years with lower discharge) and spatially (e.g., if the location of large concentrations of predatory fishes changes based on discharge).

Table ES-5
Objectives, Hypotheses, and Results Related to Density of Predatory Fishes

Year	Objectives	Hypothesis Number	Hypotheses	Results
2011–2012	Determine whether environmental variables are associated with changes in large-fish densities at the HOR study area.	$H14_0$	The density of large fish (> 30 cm in total length, i.e., potential predators) at the HOR site is not correlated with environmental variables (discharge, water temperature, turbidity, ambient light level, and small-fish density [representing availability of potential prey]).	Down-looking and side-looking hydroacoustics: Null hypothesis not supported for discharge (negative relationship with large-fish density) and water temperature (positive relationship with large-fish density). Null hypothesis accepted for other variables.
2011–2012	Determine whether there are broad-scale environmental influences on predatory fish densities at the HOR study area that result in similar changes in density to reference sites.	$H15_0$	Changes in the density of large fish (> 30 cm in total length, i.e., potential predators) at the HOR study area during the spring are not correlated with changes in density at three reference sites.	Down-looking hydroacoustics: Accept null hypothesis for two of three comparisons; reject null hypothesis for the remaining comparison (positive correlation in density between the HOR study area and the reference sites). Side-looking hydroacoustics: Reject null hypothesis for two of three comparisons (positive correlations in density between HOR study area and reference sites); accept null hypothesis for the remaining comparison.
2011–2012	Determine whether predatory fish density at the HOR study area is greater than at similar reference sites.	$H16_0$	The density of large fish (> 30 cm in total length, i.e., potential predators) at the HOR study area during the spring is not significantly different from density at three reference sites.	Down-looking hydroacoustics: Accept null hypothesis for two of three comparisons; reject null hypothesis for the remaining comparison (significantly greater density at the HOR study area than at one reference site). Side-looking hydroacoustics: Reject null hypothesis for two of three comparisons (significantly greater density at the HOR study area than at two reference sites); accept null hypothesis for the remaining comparison.

Notes: cm = centimeters; HOR = Head of Old River
Source: Present study

ES.3 RECOMMENDATIONS

Several recommendations for future study are provided to advance the findings of the present study (Table ES-6). With respect to juvenile salmonid routing and barrier effects, it is recommended that the cost and benefit of barriers at the HOR study area be studied relative to the cost and benefits of alternative management strategies, particularly non-engineering solutions such as habitat restoration (e.g., floodplain restoration and other actions proposed under the Bay Delta Conservation Plan [BDCP]). This recommendation is made for the following reasons:

- None of the barriers that were studied provided overall efficiency (O_E) greater than 62% and less than 21% mortality (see Table ES-1 for the proportion of fish remaining in the San Joaquin River and Table ES-3 for the results of sample proportion eaten in 2009-2012);
- Recent studies concluded that the San Joaquin River may not necessarily be the best migration route for juvenile salmonid survival (SJRGA 2011, 2013; Buchanan et al. 2013); and
- Survival through the south Delta generally is low by any route, suggesting that habitat improvements and restoration are desirable regardless of any routing influenced by a barrier at the HOR.

Table ES-6
Recommendations for Future Study

Juvenile Salmonid Routing Including Barrier Effects
► Study the costs and benefits of barriers in relation to alternative (non-engineering) management strategies. ► Conduct additional integrated analysis of existing data using supplementary techniques. ► Investigate new physical barrier alternatives to the rock barrier and BAFF.
Predation on Juvenile Salmonids Including Barrier Effects
► Further examine predation classification. ► Study the feasibility of physical habitat reconfiguration. ► Conduct a pilot predatory fish relocation study. ► Study the effects of physical barriers on predation hotspots. ► Study potential effects of changing recreational fishing regulations.
Behavior and Density Changes in Predatory Fishes
► Assess movement patterns of predatory fish as part of a pilot predatory fish relocation study. ► Assess predatory fish density in relation to predation hotspots.
Notes: BAFF = Bio-Acoustic Fish Fence (Fish Guidance Systems Ltd., Southampton, UK) (non-physical barrier). Source: Present study

The generally limited effectiveness of the BAFF (Tables ES-1 and ES-2), coupled with what appeared to be relatively high predation with installation of the 2012 rock barrier, leads to the recommendation to study alternative physical barriers. In this regard, it is recommended to consider the suggestions made by the VAMP's review panel (Hankin et al. 2010) about the features of such a barrier, particularly because of the BDCP's proposal to construct an operable gate at the HOR. As part of such studies of physical barriers, it is recommended that juvenile Chinook salmon survival through the Delta by the San Joaquin and Old river routes be studied further. Historically, the San Joaquin River was the safer route (reviewed by Hankin et al. 2010) but survival by

the Old River route has been similar to or higher than the San Joaquin River route since 2010 (SJRGA 2011, 2013; Buchanan et al. 2013).

Additionally, it is recommended that the existing juvenile salmonid routing data undergo additional analysis, using techniques supplementary to the univariate approach used in the present study (e.g., GLM). The purpose of such additional analysis would be to elucidate further barrier effectiveness across ranges of environmental variables and provide outputs that may support present analyses or provide a different interpretation than the current approach. It is also recommended that additional analyses be undertaken of data collected in 2013 (i.e., from the study similar to the VAMP's release of tagged juvenile Chinook salmon and from tagged steelhead released as part of the 6YSS mandated by the NMFS [2009] OCAP BO). Such analyses would allow comparison of juvenile salmonid routing and survival with a low-discharge, no-barrier treatment (i.e., 2013) with the other years (2009–2012) included in the present evaluation.

With respect to predation on juvenile salmonids, a key uncertainty warranting further research is the actual fate of fish that have been classified as having been preyed upon or having survived passage through the HOR study area. Therefore, it is recommended that the 2009–2012 data from the HOR study area be examined for the correspondence between qualitative fate classification (as used in the present investigations) and classifications based on mixture models that use data from tagged predatory fishes (e.g., from Georgiana Slough or, preferably, from the HOR study area). It is also recommended that predation classification in future studies (by mixture models, qualitative fate classification, or other means) at the HOR study area incorporate the use of the new predation tag technology (e.g., HTI's Predation Tag) that is currently being tested by DWR and its partners.

The preponderance of stationary juvenile salmonid acoustic tags in the scour hole and the association of predatory fishes with the scour hole and adjacent areas at the HOR study area leads to the recommendation that a study be undertaken of the feasibility of reconfiguring the physical habitat (e.g., modifying the scour hole's bathymetry by filling). Regardless of the presence or absence of a barrier at the HOR study area, predation was high in all years—bioenergetics modeling completed as part of this evaluation suggested that the estimated predation rates were reasonable—and a pilot predatory fish relocation study may be warranted. Such a study is already proposed for 2014–2017 and, together with any such future studies, will serve to inform management at the HOR study area and other predation hotspots.

At the broader scale, it is also recommended that changes to fishing regulations be studied to assess their potential for improving juvenile salmonid survival from the San Joaquin River region through the south Delta area, including the HOR study area. Associated with the pilot predator-relocation studies, it is recommended that broad-scale movement patterns of relocated predatory fishes also be studied. It is recommended that, at the broader scale of the south Delta, the study of the physical barriers recommended above be coupled with both the study of the locations of predation hotspots and the density of predatory fishes at hotspots, to assess the extent to which these vary under differing discharge conditions and the location of the tidal transition zone.

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1 INTRODUCTION

1.1 BACKGROUND

The California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation) manage the State Water Project (SWP) and Central Valley Project (CVP), respectively, with the goal of improving abundance, productivity, and diversity of anadromous salmonids subject to the terms of the National Marine Fisheries Service's (NMFS) 2009 Biological Opinion (BO) and 2011 amendments regarding the Long-Term Central Valley Project and State Water Project Operations Criteria and Plan (OCAP). Action IV.1.3 of the NMFS's 2009 BO instructs these agencies to "consider engineering solutions to further reduce diversion of emigrating juvenile salmonids to the interior and southern Delta,[1] and reduce exposure to CVP and SWP export facilities." Specifically, one objective of Action IV.1.3 is to "prevent emigrating salmonids from entering channels in the south Delta (e.g., Old River, Turner Cut) that increase entrainment risk to Central Valley steelhead migrating from the San Joaquin River through the Delta."

Returning adult fish of the Distinct Population Segment (DPS) of California Central Valley steelhead (*Oncorhynchus mykiss*) and Central Valley fall-run Chinook salmon (*O. tshawytscha*) utilize the San Joaquin River and its connecting interior and south Sacramento-San Joaquin Delta (Delta) tributaries during their upstream spawning migration, while juveniles use these waterways to move downstream during their emigration to the Pacific Ocean. Increased susceptibility to entrainment and predation at DWR's and Reclamation's water export facilities has been associated with juvenile salmonids moving into Old River in comparison to those juveniles remaining in the mainstem of the San Joaquin River (Holbrook et al. 2009; SJRGA 2011, 2013). In an effort to reduce the movement of juvenile salmonids into Old River, engineering solutions (e.g., barriers) have been tested at the Head of Old River (HOR) pursuant to Action IV.1.3 of the NMFS BO. While a seasonal barrier in the fall has been part of California' protective fish management measures since 1968 (Hallock et al. 1970), deployment of a springtime barrier is more recent at this location (1992) and uncertainties remain about its performance and effectiveness.

The purpose of this report is to contribute to the required BO Action IV.1.3 by evaluating and summarizing the effects of non-physical barrier (2009, 2010), no barrier (2011), and physical barrier (2012) treatments and assess their effectiveness at retaining juvenile salmonids in the mainstem San Joaquin River. Analyses include the effectiveness of the barrier treatments on juvenile salmonid route fate as influenced by the abiotic factors of light level, water temperature, discharge, and turbidity. These studies were augmented by investigations into the predation rates, predatory fish density, and predatory fish behavior that occurred in the vicinity of the HOR study area. Recommendations for future analyses and studies are identified.

1.1.1 SALMONID SPECIES MIGRATING PAST HEAD OF OLD RIVER

The two salmonid species of primary concern for the HOR studies were California Central Valley steelhead and Central Valley fall-run Chinook salmon (herein steelhead and Chinook salmon). For both species, the outmigrating juvenile life stage was most at risk at the study area. As the outmigrating juvenile salmonids pass the study area, they could remain in the San Joaquin River, shown by previous studies to be the safer route. Brandes

[1] Further detail of the study area is provided in Chapter 2, "Study Area and Focal Fish Species." Additional detail is provided in Appendix A, "Additional Background on the Study Area and Nearby Areas."

and McLain (2001) showed that recovery rates of tagged juvenile Chinook salmon at Chipps Island (Suisun Bay, Solano County, California) between 1985 and 1990 were higher if they were released in the mainstem San Joaquin River compared to being released in Old River. Additionally, they found that recovery rates from the Pacific Ocean were higher for these same fish released between 1986 and 1990 at Dos Reis (mainstem San Joaquin River downstream from the HOR study area) compared to those released in Old River (downstream from the HOR study area). Therefore, two sets of independent estimates appeared to indicate that migration down the San Joaquin River resulted in higher survival rates for juvenile Chinook salmon compared to those that migrated down Old River. Newman (2008) also found increased survival in the San Joaquin River over the Old River route.

Although juvenile salmonids taking the San Joaquin River route were documented to remain in the San Joaquin River at the HOR study area, they could also move into the interior Delta and to the Harvey O. Banks Pumping Plant (SWP) and C.W. "Bill" Jones Pumping Plant (CVP) through other downstream junctions (i.e., Turner and Columbia cuts, Old and Middle rivers). While referred to as the San Joaquin River route, it is acknowledged that fish can move from that route into Old River farther downstream. Alternatively, the juvenile salmonids could pass into Old River and traverse a route that would bring them closer to potential entrainment at the SWP and CVP pumping plants, both substantial water diversions. A third possible fate was that the juvenile salmonids could be subject to mortality (likely predation) near the HOR study area.

CHINOOK SALMON

The only Chinook salmon run in the San Joaquin River during the 2009–2012 study was the fall-run (see Section B.1.2, "Chinook Salmon—Fall-Run," in Appendix B, "Focal Fish Species Information"). Fall-run Chinook salmon are not listed under the federal Endangered Species Act (ESA). Fall-run spawn in Central Valley water courses primarily during October through December, and most of the juvenile Chinook salmon migrate to the Pacific Ocean in spring (NMFS 2013: Figure 1; Vogel and Marine 1991).

The San Joaquin River Restoration Program (SJRRP) conducted the first release of juveniles of an experimental spring-run juvenile Chinook salmon population in spring 2014 (NMFS 2013; Reclamation 2014; SJRRP 2012). Central Valley spring-run Chinook salmon were listed in 1999 as threatened under the ESA (Federal Register 64: 50394–50415; Federal Register 70: 37160-37204). A non-physical or physical barrier at the HOR could deter these spring-run juveniles from entering Old River. With the release of juveniles in 2014, spring-run adults may ascend the San Joaquin River passing through the HOR study area as early as 2016. The spawning migration of spring-run adult Chinook salmon may be affected by the operation of a barrier present at the HOR from April through June, the period during which barrier(s) would be installed.

CENTRAL VALLEY STEELHEAD

Steelhead were listed as threatened in 1998 (Federal Register 63: 13347–13371) (see Section B.1.4, "Steelhead," in Appendix B). Steelhead spawning peaks from December through April (McEwan 2001). Juveniles aged 1+ to 3+ move through the Delta (McEwan and Jackson 1996) toward the Pacific Ocean from November through June (Reclamation 2004b: Table 4-1). A barrier at HOR operated from April through June could affect juvenile steelhead migrating to the ocean during this period.

Because of its threatened status, interest in protecting juvenile steelhead has risen in recent years. Thus, the evaluation of the barriers installed at the HOR was extended to include steelhead in 2011. Two years (2011, 2012)

of data collection and analyses included juvenile steelhead. These data allowed determination of the proportion of juvenile steelhead that remained in the San Joaquin River at the HOR study area when no barrier was present in 2011, and the proportion that remained in the San Joaquin River with a physical rock barrier installed in 2012.

1.1.2 TYPES OF BARRIERS

Barriers that deter fish movement fall in two primary categories: non-physical and physical.

Non-physical barriers do not rely on physically obstructing fish from entering waterways, instead, these barriers take advantage of behavioral patterns of avoidance or attraction. Non-physical barriers offer the advantage of deterring fish from undesirable locations without physically blocking waterways (Noatch and Suski 2012) which can be important hydraulically, from a water quality perspective, and to navigation. Some types of behavioral barriers include electric (Savino et al. 2001), louvers (Kynard and Buerkett 1997), strobe lights (Anderson et al. 1998), bubble curtains (Sager et al. 1987), noise (Knudsen et al. 1992), or combinations of some of these stimuli (e.g., Perry et al. 2012).

Physical barriers do not rely on fish behavior, but exclude entry by obstructing passage. Physical barriers are the most commonly used type of fish barrier (Katapodis et al. 2004). Some physical barriers (e.g., wedgewire screens) have been important in demonstrating that fish protection can be provided at a screening location (State of Wisconsin 2003).

NON-PHYSICAL BARRIERS

Perry et al. (2012) found that the OVIVO™ Bio-Acoustic Fish Fence (BAFF) (Fish Guidance Systems, Southampton, United Kingdom) comprising an acoustic deterrent stimulus enclosed within a bubble curtain and illuminated by strobe lights, decreased the entrainment of juvenile Chinook salmon into Georgiana Slough (Sacramento County, California). Entrainment was 22.3% with the BAFF turned off, but decreased to 7.7% with the BAFF on. The mainstem Sacramento River route previously was shown to be a safer route to the Pacific Ocean than emigrating via Georgiana Slough (Perry et al. 2010). Perry et al. (2012) also found that the effectiveness of the BAFF decreased with increasing river discharge, suggesting the concomitant increase in discharge velocity was more likely to force fish through the barrier compared to lower discharge/velocity conditions.

Elsewhere, Welton et al. (2002) found a large proportion of juvenile Atlantic salmon (*Salmo salar*) were deterred by a BAFF in the River Frome, United Kingdom. Furthermore, the BAFF diverted a higher proportion of juvenile Atlantic salmon at night than during the day.

Flammang et al. (2013) reported that a BAFF deterred walleye (*Sander vitreus*) and also suggested that the strobe light was not an important part of the deterrent. The sensitivity of walleye to a strobe light may be substantially different from other fish species. Chinook salmon deterrence may be enhanced by a strobe light (Bowen et al. 2010: Table 5).

Ruebush et al. (2012) concluded that a sound/strobe/bubble barrier (similar to the BAFF described herein) could be used as a deterrent for two Asian carp species: bighead carp (*Hypophthalmichthys nobilis*) and silver carp

(*H. molitrix*). However, those authors suggested the sound/strobe/bubble barrier should not be used as an "absolute" barrier to keep these carp species from extending their range.

PHYSICAL BARRIERS

The San Joaquin River Group Authority (SJRGA 2006) found that a physical barrier constructed of rock installed at the HOR appeared to increase juvenile Chinook salmon survival from Mossdale or Durham Ferry to Jersey Point, San Joaquin River, Contra Costa County, California (SJRGA 2006: Figure 5-19) using recapture recoveries of fish collected at Chipps Island and Antioch. However, it is difficult to determine conclusively whether the rock barrier improved survival using the Pacific Ocean recapture recovery information alone (SJRGA 2006).

The SJRGA (2006) evaluated survival data for south Delta releases to Jersey Point between 1989 and 2005, including three estimates with the rock barrier installed at the HOR in 1997. The recovery rate estimates for groups released upstream of the HOR study area (Mossdale) and downstream of the study area (Dos Reis) were similar. These results supported previous conclusions that survival was increased with the rock barrier installed. In addition, the SJRGA (2007) showed that an increase in juvenile Chinook salmon survival occurred with higher discharge of the San Joaquin River.

However, if management actions were implemented to increase the discharge of the San Joaquin River with a rock barrier installed, there might be unintended consequences on ESA-listed fishes. For example, there is evidence that positive Old River flows in April and May could benefit delta smelt (*Hypomesus transpacificus*) by reducing entrainment at south Delta diversions (Lichatowich et al. 2005). One compromise between these competing demands for discharge could be to increase the number or size of the culverts placed in the rock barrier installed at the HOR.

The physical rock barrier studied in 2012 that was included in the present study was similar to those investigated by Brandes and McLain (2001) and the SJRGA (2003, 2006, 2007). All of these physical barriers were temporary obstructions installed across the entire channel width of Old River in March or April and removed in June (see Chapter 4, "Barrier Descriptions").

1.2 STUDY DESIGN, OBJECTIVES, AND HYPOTHESES

1.2.1 STUDY DESIGN

BACKGROUND

The present study used a partially controlled experimental design with uncontrollable exogenous factors influencing the treatment conditions. The principal focus of the study was the effects of barriers to influence juvenile salmonid routing (see Section 1.2.2, "Juvenile Salmonid Routing Including Barrier Effects"). The controlled portion of the design was the selection of treatments for the March through June period in each of the years studied (2009 through 2012): a non-physical barrier (BAFF) in 2009 and 2010; no barrier in 2011; and a physical barrier (rock) in 2012. The "no barrier" condition provided information about the proportion of juvenile salmonids entering Old River in the absence of a barrier. Because no barrier was present, 2011 provided a reference condition, but it was not a control condition for 2009, 2010, or 2012 because of major differences in exogenous factors between those years, in particular, discharge.

A number of physical factors were identified as parameters that may have influenced salmonid behavior in the various treatments. These parameters were discharge, water velocity, water temperature, light level, and turbidity. Variability in discharge, water velocity, water temperature, and turbidity from 2009 through 2012 is discussed in Chapter 3, "Physical Parameters."

The effectiveness of retaining juvenile salmonids in the San Joaquin River between barrier treatments was evaluated through acoustic telemetry. In each year, acoustic transmitters (tags), either Hydroacoustic Technology, Inc. (HTI) (Seattle, Washington) or VEMCO (Bedford, Nova Scotia, Canada) were implanted into juvenile Chinook salmon and/or steelhead. Movement patterns of the tagged juvenile salmonids were tracked by hydrophone arrays deployed in or near the HOR study area.

For the HTI equipment, the hydrophone array was deployed within the HOR study area from April through June during all the study years (2009-2012). The tagged juvenile Chinook and steelhead were released 24.4 kilometers (km) upstream from the HOR study area at Durham Ferry State Recreation Area. As the tagged juvenile salmonids moved through the area of the divergence, the HTI hydrophones recorded two-dimensional (2D) tracks, and these tracks were used to derive measures of juvenile salmonid routing, including barrier effects and predation rates on juvenile salmonids.

Previous publications (Bowen et al. 2012; Bowen and Bark 2012) reported results of BAFF deterrence and efficiency at the HOR study area during 2009 and 2010. The present study provides reanalysis of these same data, but reclassifies all juvenile Chinook salmon fates into samples based upon the barrier status (i.e., BAFF on/off no barrier, rock barrier) and environmental conditions (i.e., light level and velocity). Earlier publications relied on analysis of experimental groups based on the release time of the tagged juvenile salmonids from Durham Ferry without respect to the abiotic environmental conditions encountered when the tagged salmonids arrived at the HOR study area. A reanalysis approach was applied to all data (2009-2012) evaluated in this report. All tagged juvenile salmonids were grouped into samples based on the conditions when the fish arrived at the HOR study area. This approach was applied to both HTI and VEMCO tag detection data sets.[2]

In association with the main studies of juvenile salmonid routing and predation, investigation of predatory fishes was also undertaken in 2011 and 2012, using acoustic tagging and mobile hydroacoustic surveys (see Section 1.2.4, "Behavior and Density Changes in Predatory Fishes").

METRICS OF EFFICIENCY

HTI equipment (i.e., transmitters, hydrophones, and receivers) was deployed from 2009-2012, and measures of barrier efficiency and salmonid behavior were derived from the time-stamped tag detections arriving at different hydrophones.

The first measure of barrier efficiency determined using HTI equipment for 2009-2012 was Overall Efficiency (O_E) (see equation in Chapter 5, "Methods"). O_E was defined as the total number of tags implanted into juvenile Chinook salmon determined to have passed by the HOR study area and continued down the San Joaquin River divided by the total number of tags that arrived at the HOR study area. O_E was calculated in the same manner for steelhead.

[2] Comparisons between HTI and VEMCO data are provided in Appendix C.

A second measure of barrier efficiency was developed for 2009-2012 because the 2D tracks made behavioral analysis possible, and was defined as Protection Efficiency (P_E). A set of rules was developed that defined when a 2D tag track exhibited very strong evidence that the juvenile salmon implanted with that tag had been eaten (Appendix E, "Fish Fate Determination Guidelines"). When a tagged juvenile salmonid was classified as having been eaten, it was removed from analysis of P_E. Only surviving "tags-in-salmonids" remained in the data sets. The P_E was calculated as the number of surviving tagged juvenile salmonids determined to have passed by the HOR study area and continued down the San Joaquin River, divided by the sum of surviving tags-in-salmonids that passed out of the HOR study area through either the San Joaquin or Old rivers.

A third measure of BAFF efficiency was developed using the 2D tracks for 2009-2010 and was termed Deterrence Efficiency (D_E). As each tagged juvenile Chinook salmon approached the BAFF line, its path was determined to have been either deterred or undeterred by the BAFF. The determination of deterrence was made with the status of the BAFF on and off. With the BAFF off, the physical infrastructure of the BAFF remained in the water but the BAFF was not in operation.

For the 2009 through 2012 data sets, a measure of predation was developed using the 2D tracks, termed proportion eaten. The fate of each tagged juvenile Chinook salmon was assessed according to the rules described in Appendix E, "Fish Fate Determination Guidelines." The determination of predation was made by the judgment of two experts. Uncertainties associated with the expert assessments are explored in Chapter 7, "Discussion." After the predation fate had been assessed, the population proportion eaten was determined and defined as the quotient of the number of juveniles eaten divided by the total number passing through the HOR study area. Next, the proportion eaten in each sample group (see "Grouping Juvenile Salmonid into Samples" in Section 5.2.1) was used for hypothesis testing.

In addition to the sample-based metrics of proportion eaten that was investigated with univariate hypothesis testing, analyses based on the fates of individual juvenile salmonids evaluated as the probability of predation also were conducted (see Section 1.2.3, "Predation on Juvenile Salmonids Including Barrier Effects").

1.2.2 JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

PRIMARY OBJECTIVES AND HYPOTHESES RELATED TO JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

The objectives in this section relate to the effectiveness of the barriers as management tools to keep juvenile salmonids from entering Old River, in compliance with NMFS (2009, 2011) Action IV.1.3. The objectives are enunciated as hypotheses and they are listed in Table 1-1.

Non-physical Barrier - BAFF (2009 and 2010)

In 2009, a BAFF was operated from April 20 to May 26, and tagged juvenile Chinook salmon passed through the HOR study area from April 23 to May 18. The status of the BAFF alternated between off and on so that, approximately 50% of the time, it was operational. Exact BAFF operation times may be found in Bowen et al. (2012: Table 1). This time split between off/on operation also allowed approximately 50% of the tagged juvenile Chinook salmon to experience the BAFF when in operation.

In 2010, a BAFF was operated from April 15 to June 15, and tagged juvenile Chinook salmon passed through the HOR study area from April 27 to May 20. Similar to 2009, the status of the BAFF alternated between on and off so that it was operational approximately 50% of the time. Exact operation times may be found in Bowen and Bark (2012: Table 2). This time split between on/off operation allowed approximately 50% of the tagged juvenile Chinook salmon to experience the BAFF when in operation. In 2009 and 2010, no steelhead were surgically implanted or released.

The goal of the analysis was to determine if the BAFF was effective in retaining a significant proportion of the juvenile Chinook salmon in the San Joaquin River. If the BAFF retained a significant proportion, then it could be an effective deterrent. Hypotheses numbered $H1_0$, $H2_0$, $H3_0$, and $H4_0$ were tested to measure O_E, P_E, and D_E to determine BAFF efficiency (Table 1-1).

Table 1-1
Objectives and Hypotheses Related to Juvenile Salmonid Routing Including Barrier Effects

Year and Treatment	Objective	Hypothesis Number	Hypotheses
2009 BAFF	Determine whether barrier efficiency (O_E, P_E, and D_E) for juvenile Chinook salmon was improved by BAFF operation.	$H1_0$	For juvenile Chinook salmon, barrier efficiency (O_E, P_E, and D_E) with the BAFF on was equal to barrier efficiency with the BAFF off.
2010 BAFF	Determine whether barrier efficiency (O_E, P_E, and D_E) for juvenile Chinook salmon was improved by BAFF operation.	$H2_0$	For juvenile Chinook salmon, barrier efficiency (O_E, P_E, and D_E) with the BAFF on was equal to barrier efficiency with the BAFF off.
	Determine whether BAFF barrier efficiency with the BAFF on changed significantly between years.	$H3_0$	For juvenile Chinook salmon with BAFF on, barrier efficiency (O_E, P_E, and D_E) barrier efficiency in 2009 was equal to barrier efficiency in 2010.
	Determine whether with the BAFF off, barrier efficiency changed significantly between years.	$H4_0$	For juvenile Chinook salmon with BAFF off, barrier efficiency (O_E, P_E, and D_E) in 2009 was equal to barrier efficiency in 2010.
2011 No Barrier	Determine whether and to what extent the BAFF infrastructure affected O_E and P_E when the BAFF was turned off.	$H5_0$	For juvenile Chinook salmon, O_E and P_E were equal for 2009 BAFF off, 2010 BAFF off, and 2011 no barrier conditions.
	Determine whether juvenile Chinook salmon and steelhead had the same O_E and P_E through the HOR study area.	$H6_0$	O_E and P_E were the same for juvenile Chinook salmon and steelhead.
2012 Rock Barrier	Compare OE and PE across treatments to determine whether any barrier was more effective than no barrier and which produced the highest efficiency at retaining juvenile Chinook salmon in the San Joaquin River.	$H7_0$	For juvenile Chinook salmon, O_E and P_E were equal for 2009 and 2010 BAFF on, 2011 no barrier, and 2012 rock barrier treatments.

Notes: BAFF = Bio-Acoustic Fish Fence (Fish Guidance Systems Ltd., Southampton, UK); D_E = deterrence efficiency; HOR = Head of Old River; O_E = overall efficiency; P_E = protection efficiency; Barrier Efficiency = O_E, P_E, and D_E

Source: Present study

No Barrier (2011)

In 2011, no barrier was operated although both tagged juvenile Chinook salmon and steelhead passed through the HOR study area from May 4 to June 22. Using information collected by the hydrophone array, two measures of efficiency were obtained from the 2011 data. O_E and P_E were determined with exactly the same method mathematically (see Chapter 5, "Methods") as the barrier efficiency in years with barriers present.

Determining whether the BAFF infrastructure alone affected the routing of juvenile Chinook salmon is most appropriate when compared with the no barrier treatment (2011). Therefore, one hypothesis tested (Table 1-1: $H5_0$) if O_E and P_E varied between the status when the BAFF was installed but not in operation and when there was no barrier.

It also needed to be determined whether the routing of tagged juvenile Chinook salmon and steelhead were the same in a year in which no barrier was installed. Hence, hypothesis $H6_0$ tested if there was a difference between tagged juvenile Chinook salmon and steelhead for O_E and P_E (Table 1-1).

Physical Barrier - Rock (2012)

In 2012, a physical barrier made of rock was installed and operated from April 1 through May 31, and tagged juvenile Chinook salmon and steelhead passed through the HOR study area from April 28 through May 29. In contrast to BAFF operations, the physical barrier located at the HOR was always operational (on) because it could not be turned off or uninstalled.

It needed to be determined how the barrier treatments performed relative to each other and relative to no barrier. For example, if the physical rock barrier retained a significant proportion of the juvenile Chinook salmon in the San Joaquin River, then it might be an effective deterrent. Hence, one hypothesis tested measures O_E and P_E to determine the routing proportions with different treatments and discharge regime (Table 1-1: $H7_0$).

SUPPORTING HYPOTHESES RELATED TO JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

DWR (2012) studied the effect of a BAFF under variable velocity conditions. A substantial proportion of the juvenile Chinook salmon were deterred by the BAFF under both low (<0.25 meters per second [m/s] "fish escape" velocity (Figure 4-2) and high (<0.25 m/s "fish escape" velocity) velocity (DWR 2012: Table 3-12). In addition, for the BAFF on status, O_E, P_E, and D_E were all greater under low-velocity compared to high-velocity conditions. These results suggest that the BAFF's effectiveness at the HOR study area might also be affected by discharge/velocity. As previously noted, Perry et al. (2012) also found that the effectiveness of the BAFF was inversely related to discharge. Perry et al. (2012) suggested that higher discharges and correspondingly higher velocities were more likely to force fish through the barrier compared to lower discharge/velocity conditions.

DWR (2012) described studies of a BAFF at Georgiana Slough (Sacramento County, California). This was the same BAFF studied by Perry et al. (2012). A significant proportion of juvenile Chinook salmon were deterred by the BAFF under both low (< 5.4 lux) and high (≥ 5.4 lux) light conditions (DWR 2012: Table 3-11). However, for the BAFF "on" status, D_E under high-light conditions was 13.7% greater than the D_E under low-light conditions. The results from the Georgiana Slough study suggest that the BAFF's performance at the HOR study area may be affected by ambient light level similar to the findings of Welton et al. (2002).

Because of these findings, the effects of light level and water velocity on O_E, P_E, and D_E were studied and are reported herein. For each hypothesis, where possible, analyses were conducted at various light and discharge/velocity levels. These analyses showed whether or not the O_E, P_E, and D_E were affected by these abiotic environmental variables and if so, to what extent.

1.2.3 PREDATION ON JUVENILE SALMONIDS, INCLUDING BARRIER EFFECTS

Several major objectives of the present study are related to predatory fish ecology and predation at the HOR study area. The HOR area and the scour hole downstream of the divergence of San Joaquin and Old rivers were previously noted as regional "hotspots" of high predation, although recent studies do not concur (e.g., SJRGA 2010, 2011, and 2013, and references therein). In the 2009 study of BAFF deterrence, Bowen et al. (2012) noted that predation was intense in the HOR area and appeared associated with the scour hole just downstream of the divergence of Old River from the San Joaquin River. They concluded the following (Bowen et al. 2012: 20–21):

> The data suggest that much of the gains accomplished by the BAFF's determent of juvenile Chinook salmon are offset by the predatory fishes inhabiting the scour hole. We recommend that if the BAFF is installed in the future that predator relocation be employed near the Old River barrier area. For example, striped bass and largemouth bass could be moved from the HOR study area to San Luis Reservoir. Failure to do so could lead to a high predation rate situation and the highly efficient BAFF's deterrence may be offset by the heavy predation in the scour hole.
>
> It is possible that the high 2009 predation rates observed were a function of the low discharge (dry year) in the San Joaquin River. Juvenile Chinook salmon and predators might have been concentrated into a smaller habitat area due to the reduced volume of water than during average or wet years. Such a concentration could result in higher encounter rates between predators and juvenile Chinook salmon leading to an increased predation rate.

The predation rate on tagged juvenile Chinook salmon in the HOR was also high in 2010, despite greater river discharge (Bowen and Bark 2012).

In the present study, predation was examined using a sample-based, univariate approach (proportion eaten) and a generalized linear modeling (GLM) approach (probability of predation). Perspective on rates of predation suggested by tagged juvenile salmonids was provided with bioenergetics modeling of potential predatory fish consumption of prey fish (see Appendix H, "Illustrative Example of Striped Bass Predation Using Bioenergetics Modeling").

OBJECTIVES AND HYPOTHESES RELATED TO PROPORTION OF JUVENILE SALMONIDS EATEN

Because of the importance of predation in affecting the usefulness of a fish barrier, various hypotheses were tested regarding the proportion of juvenile salmonids entering the HOR study area that were determined to have been eaten based on the aforementioned "predation rules" (see Appendix E, "Fate Determination Guidelines"). In addition to this hypothesis testing approach based on proportions of juvenile salmonids entering the HOR study area that were eaten (grouping juvenile salmonids into samples, and using univariate statistics; see Section 5.2, "Evaluation of Juvenile Salmonid Routing Including Barrier Effects"), an approach based on the probability of

predation of individual fish entering the HOR study area from GLM also was used (see "Objectives and Hypotheses Related to Probability of Predation" in the following section).

For 2009 and 2010 data analyses, it needed to be determined if the BAFF increased the proportion eaten when it was operating compared to when it was not operating. The outcome would be important in determining the effectiveness of the BAFF as a management tool. Thus, the proportion of those juvenile Chinook salmon eaten was tested as determined by expert opinion for 2009 and 2010 data separately, with the status of the BAFF on compared to BAFF off (Table 1-2: $H8_0$).

For 2011 data, it was possible to compare juvenile Chinook salmon and steelhead estimates of the proportion determined to have been eaten (Table 1-2: $H9_0$). It needed to be determined if species differences may have led to differential susceptibility to predation in the HOR study area. Differences between the species (described in Section 5.1.1, "Fish Sources and Tag Specifications," and Section B.1, "Focal Salmonid Species for Protection at Head of Old River" [Appendix B, "Focal Fish Species Information"]) in migration timing, size when in the vicinity of the HOR study area, and presumably swimming ability might all influence differences in predation probabilities.

For 2012 data analyses, the physical rock barrier was installed and all juvenile Chinook salmon that were determined to have been eaten were used to estimate the proportion eaten in each sample. It needed to be determined if the proportion eaten in each year was different, and what proportion might be eaten. For 2009 and 2010, BAFF-on observations of juvenile Chinook salmon determined to have been eaten were used. No BAFF-off observations were included. This approach simulated what would be expected if the BAFF were operated continuously. This hypothesis would identify if one of the barrier types caused a substantially higher proportion to be eaten (Table 1-2: $H10_0$).

OBJECTIVES AND HYPOTHESES RELATED TO PROBABILITY OF PREDATION

In addition to hypotheses related to proportion eaten that were tested with a univariate, sample-based approach (see "Objectives and Hypotheses Related to Proportion Eaten" previously presented), a GLM approach was used to address objectives and hypotheses related to probability of predation (Table 1-2: H11, H12, and H13). This approach allowed the probability of predation to be framed in terms of abiotic factors (light level, water temperature, turbidity, and discharge/velocity), biotic factors (juvenile size, density of large fish [assumed to be representative of predatory fish], density of small fish [assumed to be representative of alternative prey for predators]), and the presence/operational status of non-physical (BAFF) or physical barriers (rock) at the HOR study area. More detailed discussion of the underlying hypotheses is provided in Section 5.3.2 "Probability of Predation (Generalized Linear Modeling)."

Table 1-2
Objectives and Hypotheses Related to Predation on Juvenile Salmonids Including Barrier Effects

Year	Objectives	Hypothesis Number	Hypotheses
2009	Provide a direct test that the BAFF operation had some influence on proportion eaten.	$H8_0$	The proportion of juvenile Chinook salmon entering the HOR study area that were eaten with the BAFF on was equal to the proportion eaten when off.
2010	Provide a direct test that the BAFF operation had some influence on proportion eaten.	$H8_0$	The proportion of juvenile Chinook salmon entering the HOR study area that were eaten with the BAFF on was equal to the proportion eaten when off.
2011	Evaluate the proportion eaten for juvenile Chinook salmon and steelhead.	$H9_0$	The proportions of juvenile Chinook salmon and steelhead entering the HOR study area that were eaten were equal.
2009–2012	Show whether there were differences in proportion eaten between treatments.	$H10_0$	The proportions of juvenile Chinook salmon entering the HOR study area that were eaten were equal for 2009 and 2010 BAFF on, 2011 no barrier, and 2012 rock barrier.
2009, 2010, 2012	Evaluate the influence of abiotic and biotic factors, including barrier treatment/status, on probability of predation of juvenile Chinook salmon.	H11	Probability of predation of juvenile Chinook salmon is negatively related to discharge (shorter travel time/distance at higher discharge), turbidity (lower visual range of predators with greater turbidity), size (larger juveniles less susceptible to predation), and small-fish density (availability of alternative prey for predators). Probability of predation is positively related to water temperature (higher bioenergetic demands of predators with higher temperature) and ambient light level (greater visual range of predators with more light). Probability of predation is unrelated to barrier treatment/ status (BAFF on/off, rock barrier).
2011, 2012	Evaluate the influence of abiotic and biotic factors on probability of predation of juvenile Chinook salmon.	H12	Probability of predation of juvenile Chinook salmon is negatively related to discharge, turbidity, juvenile size, and small-fish density. Probability of predation is positively related to water temperature, ambient light level, and density of predatory fish (greater predation pressure with more large fish).
2011	Evaluate the influence of abiotic and biotic factors on probability of predation of juvenile steelhead.	H13	Probability of predation of juvenile steelhead is negatively related to discharge, turbidity, juvenile size, and small-fish density. Probability of predation is positively related to water temperature, ambient light level, and density of predatory fish (greater predation pressure with more large fish).

Notes: BAFF = Bio-Acoustic Fish Fence (Fish Guidance Systems Ltd., Southampton, UK); HOR = Head of Old River
Source: Present study

1.2.4 BEHAVIOR AND DENSITY CHANGES IN PREDATORY FISHES

OBJECTIVES RELATED TO BEHAVIOR OF PREDATORY FISHES

Objectives related to predatory fish behavior at the HOR study area consisted of analyses based on acoustically tagged predatory fish and mobile hydroacoustics. These analyses generally did not test specific hypotheses (although see the following section on "Objectives and Hypotheses Related to Changes in Density of Predatory Fishes") and were more exploratory and descriptive. The objectives and their utility to management are summarized in Table 1-3.

Table 1-3
Objectives Related to Behavior of Predatory Fishes at the HOR Study Area

Year	Objective	Means of Study	Utility to Management
2009–2012	Describe residence time of predatory fish.	Acoustically tagged predatory fish	May indicate turnover of predatory fish, and therefore allows inference regarding the level of effort required for relocation of predatory fish.
2009–2012	Describe areas (spatial and velocity) occupied by predatory fish.	Acoustically tagged predatory fish, mobile hydroacoustic surveys, stationary tags from juvenile salmonid (presumably eaten and defecated by predatory fish)	May indicate location within the study area to focus predator capture efforts for any contemplated relocation efforts, as well as indicates habitat areas that could be manipulated to reduce predator density and predation risk.

Note: HOR = Head of Old River
Source: Present study

OBJECTIVES AND HYPOTHESES RELATED TO CHANGES IN DENSITY OF PREDATORY FISH

Mobile hydroacoustic survey data from 2011 and 2012 were used to determine if there was evidence of changes in environmental variables associated with changes in density of large fish (>30 centimeters [cm] total length (TL), of which many are assumed to be predatory fish), by testing $H14_0$ (Table 1-4). Knowledge of the potential influence of these variables on density has the potential to guide management action (e.g., by allowing efforts such as predator relocation or reduction to be focused at times of potentially high density). In addition, two objectives related to $H15_0$ and $H16_0$ were intended to determine whether changes in density at the study area were similar to changes in the broader south Delta area, and whether the density at the study area was greater than at other areas. These objectives/hypotheses were examined by comparing density at the study area to three reference sites in the San Joaquin River (Table 1-4).

Table 1-4
Objectives and Hypotheses Related to Density of Predatory Fishes at the HOR Study Area

Year	Objectives	Hypothesis Number	Hypotheses
2011–2012	Determine if environmental variables are associated with changes in large-fish density at the HOR study area.	$H14_0$	Density of large fish (>30 cm TL) (i.e., potential predators) at the HOR site is not correlated with environmental variables (discharge, water temperature, turbidity, light level, and small-fish density [representing availability of potential prey]).
2011–2012	Determine if there are broad-scale environmental influences on predatory fish density at the HOR site that result in similar changes in density to reference sites.	$H15_0$	Changes in density of large fish (>30 cm TL) (i.e., potential predators) at the HOR site during the spring are not correlated with changes in density at three reference sites.
2011–2012	Determine if predatory fish density at the HOR site is greater than at reference sites.	$H16_0$	The density of large fish (>30 cm TL) (i.e., potential predators) at the HOR site during the spring is not significantly different from density at three reference sites.

Notes: cm = centimeters; HOR = Head of Old River; TL = total length
Source: Present study

2 STUDY AREA AND FOCAL FISH SPECIES

2.1 STUDY AREA

2.1.1 THE SACRAMENTO–SAN JOAQUIN DELTA

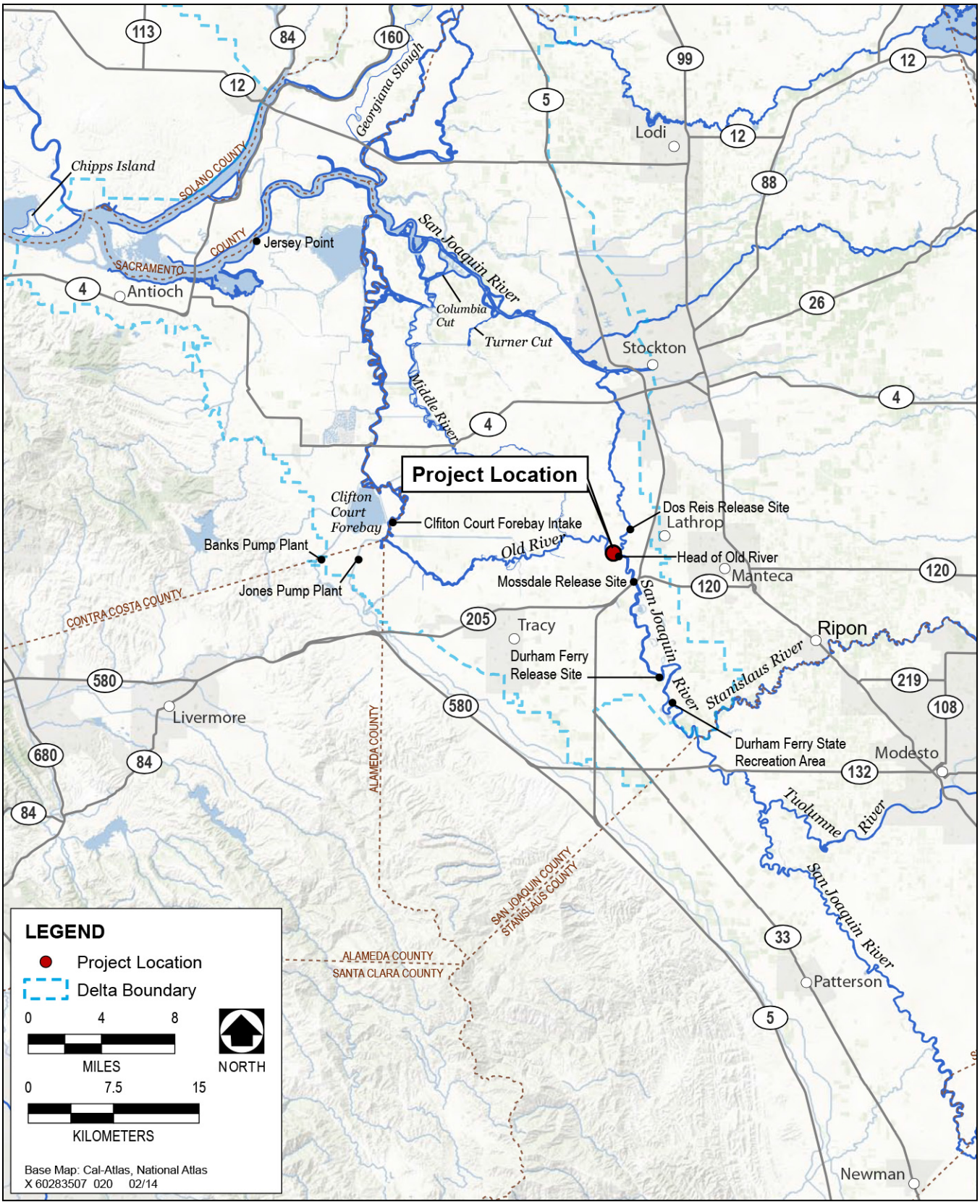
The Delta is a complex of reclaimed islands[1] and tidally influenced freshwater sloughs and channels at the confluence of the Sacramento and San Joaquin rivers. It is part of a larger estuary system to the west that includes Suisun, San Pablo, and San Francisco bays. The Delta watershed includes more than one-third of California's land surface area, and stretches from the eastern slopes of the Coast Range to the western slopes of the Sierra Nevada (Lund et al. 2007). The Delta is approximately 39 km wide and 77 km long. The Delta is located in an area roughly delimited by the cities of Sacramento, Stockton, Tracy, and Antioch (Thompson 1957) and includes portions of Sacramento, San Joaquin, Contra Costa, Solano, and Yolo counties. Before settlement and reclamation activities, the tidal basin included approximately 129,499 hectares, and another 82,961 hectares was subject to seasonal flooding (Thompson 1957).

Historically, the Delta was a natural wetland complex, fed by discharge from the Sacramento and San Joaquin rivers. The vast wetland complex consisted of tidal channels, sloughs, islands with tule (*Schoenoplectus* spp.) marsh plains, complex water channels characterized by dendritic branching, and natural levees colonized by riparian forests (Bay Institute 1998). A slow rise in sea level and gradual regional tectonic subsidence created an "accommodation space" that allowed for the continuous accumulation of large volumes of sediment within the Delta (Atwater et al. 1979; Orr et al. 2003). The Delta essentially was formed by a combination of upstream sediment deposition and the decay of large quantities of marsh vegetation (Lund et al. 2007). The formation of thick deposits of peat, capped by tidal marshes, kept up with a slow rise in sea level. Approximately 60% of the Delta land mass was flooded by daily tides, and spring tides could submerge it completely (Lund et al. 2007; Thompson 1957). Large areas frequently flooded during heavy winter rains. The interior waterways were primarily freshwater, although saltwater intrusion from the west occurred during summer months (Jackson and Paterson 1977).

Today, the Delta is a highly modified system when compared to conditions that existed before European settlement and reclamation activities. Many waterways are channelized and contained within riprap-stabilized levees. Floodplains, backwaters, and riparian vegetation are absent from many areas. The reduction of riparian vegetation and shaded riverine habitat through levee construction and protection activities has contributed to increased annual water temperatures (NMFS 2011). These changes have contributed to the decline of many native fish species while benefitting non-native fish species that are more adaptable to the highly altered environment (Lund et al. 2007; Moyle 2002). In addition, the simplified environment and loss of habitat complexity may have contributed to the success of non-native fish species and the decline of native fish populations (Moyle 2002).

Supplemental information is provided in Appendix A, "Additional Background on the Study Area and Nearby Areas," which includes information on the upstream tributaries leading to the HOR study area (Figures 2-1 and A-1).

[1] These "islands" are actually polders.



Source: Data compiled by AECOM in 2013

Figure 2-1 Location and Study Area Indicating Major Tributaries of the San Joaquin River

2.1.2 RESEARCH PROJECT STUDY AREA

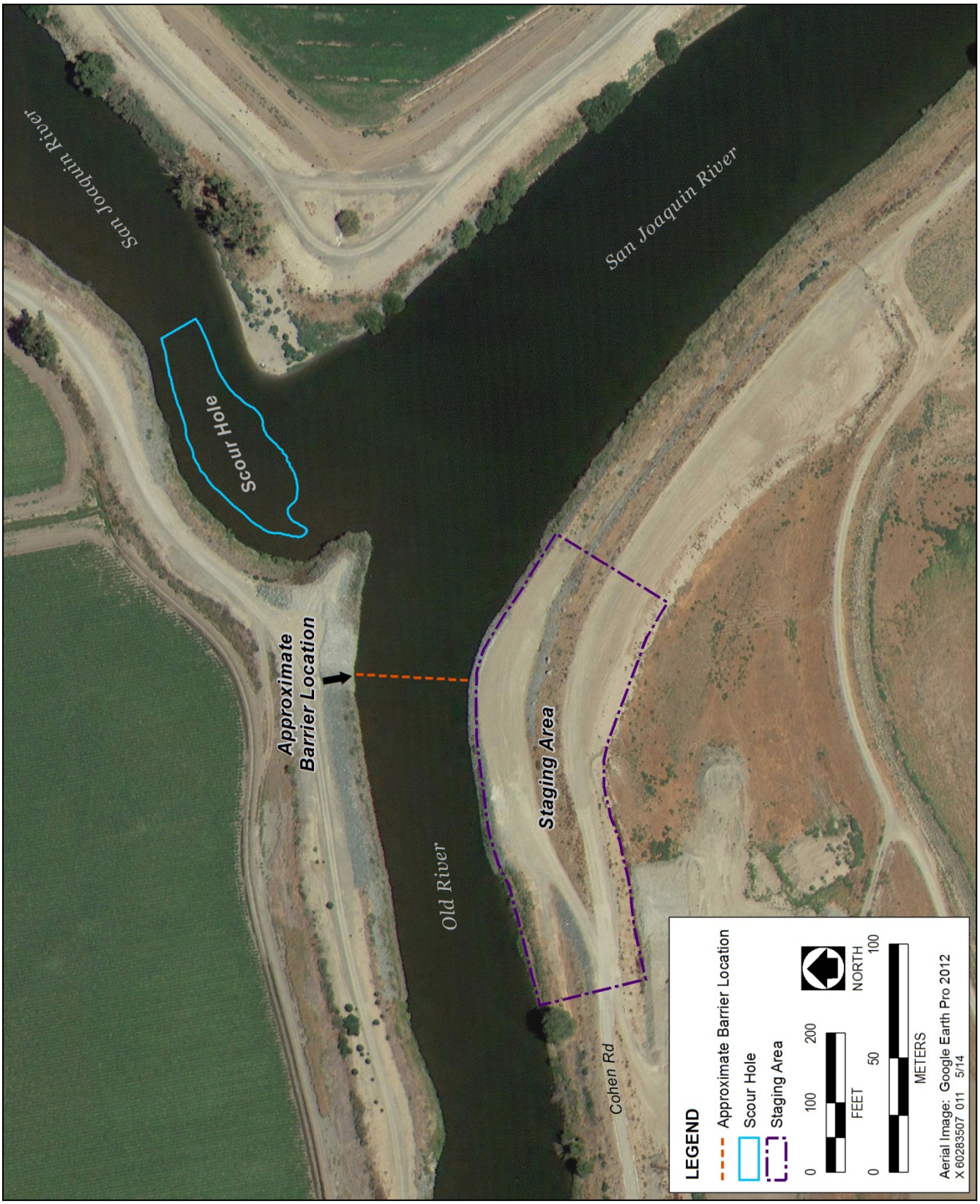
The field data collection activities of the research described in this report were conducted between April 1, 2009 and June 30, 2012, within a study area located in the southeast corner of the Delta at the divergence of the San Joaquin and Old rivers. The HOR study area boundary was delineated by the location of the most upstream and downstream hydrophones (discussed in further detail in Chapter 5, "Methods").

The primary land use is agricultural, including row crops, nut trees, dairies, and hay production. The banks of the San Joaquin River within the study area are heavily fortified with riprap with steep slopes that drop quickly to the river thalweg. Overstory riparian vegetation is absent. The river channel generally is featureless with an average depth of approximately 3 meters (m) and a maximum depth of 9 m, and the benthic substrate is composed primarily of fine sediments. Maximum depth occurs in a large scour hole, located just downstream from the divergence with Old River.

The Old River represents the first watercourse downstream of the convergences of the three main tributaries and the San Joaquin River (Figure 2-1). This divergence is the first potential migration fork for emigrating juvenile salmonids. If the Old River route is selected, it leads the juvenile salmonids into the interior Delta where susceptibility to predation and entrainment by the SWP and CVP intake pumps are increased. All emigrating juvenile salmonids produced in the San Joaquin River must pass by the HOR. Predation rates in this area may be comparatively high because:

- predatory fish densities can be particularly high in this location;
- the area is narrow and highly channelized;
- the area lacks littoral vegetation, instream structure and floodplain habitat;
- the river margins quickly become steep dropping into the river thalweg; and
- discharge patterns have created the fairly large, deep scour hole in the San Joaquin River just downstream of the divergence, which may attract predatory fish and increase their foraging opportunities (Figure 2-2).

These characteristics may create a predatory gauntlet, especially in the spring, when annual predictable high densities of juvenile salmonids are migrating downstream (Tables B-2 and B-4 in Appendix B, "Focal Fish Species Information"). Previous studies suggest that predation rates on juvenile Chinook salmon can be 12% to 40% at the HOR study area (Bowen et al. 2012; Bowen and Bark 2012). Appendix A, "Additional Background on the Study Area and Nearby Areas," briefly describes the three main tributaries of the San Joaquin River, including the current status of their steelhead and Chinook salmon populations.



Source: Data compiled by AECOM in 2013

Figure 2-2 **San Joaquin River–Old River Divergence, Scour Hole Location, Approximate Rock Barrier Line and Staging Area**

2.1.3 HEAD OF OLD RIVER

In 2009, DWR began assessing the deterrence capabilities of alternative barrier types to facilitate the retention of juvenile salmonids in the mainstem San Joaquin River during the downstream migration toward the Pacific Ocean. A non-physical BAFF barrier was installed in 2009 and 2010 at the divergence of Old and the San Joaquin rivers, approximately 5 km west of the City of Lathrop and 11 km northeast of the City of Tracy (Figure 2-3). No barrier was installed in 2011 because of very high discharge, and a physical rock barrier was installed in 2012 (Figure 2-4). Barriers were designed to improve migration conditions for juvenile salmonids that originated in the San Joaquin River watershed by blocking and/or deterring passage into Old River and directing movements to the mainstem San Joaquin River. Barrier descriptions, objectives, installation dates, and operations are summarized in Chapter 4, "Barrier Descriptions."

2.2 FOCAL FISH SPECIES

2.2.1 FOCAL FISH SPECIES FOR PROTECTION

The primary focal fish species that management intends to protect using barriers at the HOR are Chinook salmon and steelhead, both of which originate in tributaries of the San Joaquin River upstream of the HOR. Both Chinook salmon and steelhead are in long-term decline in California. Historically, the San Joaquin River supported three runs of Chinook salmon: fall, late fall, and spring (Fisher 1994). The late fall and spring-runs were extirpated in the 1940s (Fisher 1994). At present, the only Chinook salmon in the San Joaquin River region are fall-run, although spring-run are proposed for reintroduction under the San Joaquin River Restoration Program (SJRRP). Historically, steelhead were widely distributed throughout the Sacramento and San Joaquin river basins, and were composed of summer and winter-runs. Presently, only the winter-run steelhead persist in the Central Valley (Williams 2006) due to dam construction that prevents summer steelhead from reaching higher elevation stream reaches where they previously over-summered in deep, cool pools. An important period of interest for fish species protection is spring, when juvenile Chinook salmon and steelhead migrate downstream through the Delta. More detailed information on the status and life history of Chinook salmon and steelhead is presented in Section B.1, "Focal Salmonid Species for Protection at Head of Old River," in Appendix B, "Focal Fish Species Information."

In addition to the salmonid fish species for protection at the HOR, two other listed species are relevant for consideration of barrier operations: delta smelt (*Hypomesus transpacificus*) and green sturgeon (*Acipenser medirostris*). More detailed information on these two species is presented in Section B.2, "Other Species for Protection at Head of Old River," in Appendix B.

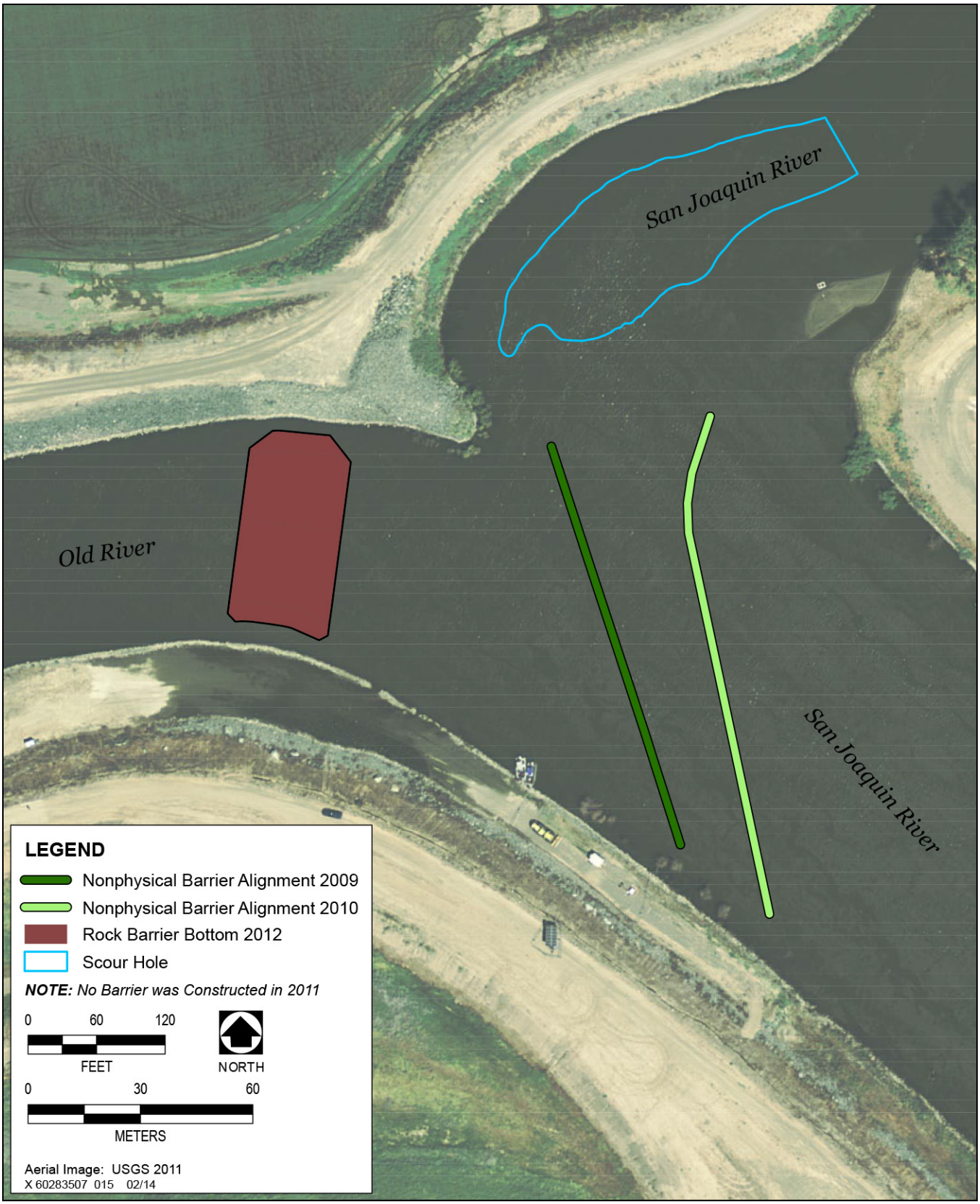
2.2.2 FOCAL PREDATORY FISH SPECIES

Several predatory fish species occur at the HOR study area and may influence barrier effectiveness if they are attracted to structures or capitalize on changed hydrodynamics or juvenile salmonid behavior that results from barrier deployment (see Bowen et al. 2012; Bowen and Bark 2012). The main predatory fish species that have been observed at the HOR study area during the studies from 2009 through 2012 are striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), channel catfish (*Ictalurus punctatus*), and white catfish (*Ameiurus catus*). A more detailed overview of the biology of the predatory fish species is provided in Section B.3, "Focal Predatory Fish Species at Head of Old River," in Appendix B.



Source: Data compiled by AECOM in 2013

Figure 2-3 Vicinity of the Head of Old River Study Area Depicting Salmonid Release Points



Sources: DWR 2012; Bianchini and Cane pers. comm. 2013; data compiled by AECOM in 2013

Figure 2-4 **Barrier Alignments near the Head of Old River, 2009–2012**

2.2.3 FOCAL FISH ASSEMBLAGE

A basic description of the spring (March through June) fish assemblage in the vicinity of the HOR study area is provided herein from three surveys: (1) trawling in the San Joaquin River at Mossdale which provides an indication of small fish relative abundance in the river channel (Dekar et al. 2013); (2) seining at three sites in the San Joaquin River which provides information on small fish in the nearshore, shallow water environment (Dekar et al. 2013); and (3) electrofishing in the San Joaquin River downstream from the HOR study area which samples small and large fish in the nearshore environment (Conrad, pers. comm., 2013). Of these surveys, Mossdale trawling occurs most frequently (near daily) at the highest intensity (generally 10 trawls per day) and is efficient at collecting the main salmonid species for protection at the HOR study area (i.e., juvenile Chinook salmon). For the summary presented next, trawl and seine data were limited to small fish (i.e., less than 150 millimeters [mm] fork length [FL]), because the trawling gear used was most suited for smaller fish. In addition, the Mossdale trawl estimates for small fish density were used in subsequent analyses of large fish abundance and salmonid juvenile predation probability, discussed in Chapter 5, "Methods." More information regarding the methods for trawling and seining is provided by Dekar et al. (2013). Electrofishing consisted of 300-meter-long transects from a survey vessel at 50 sites bimonthly from October 2008 through October 2010 (Conrad, pers. comm., 2013). Of this total effort, the spring (April and June, 2009 and 2010) data from the site (SAN_1) closest to the HOR study area are summarized herein.

RIVER CHANNEL (MOSSDALE TRAWL)

Thirty-five fish taxa were collected with trawling at Mossdale from March through June in 2009 through 2012, of which 12 were native species (Table 2-1). Daily abundance indices of small fish (less than 150 mm FL) from March through June 2009 were calculated as the geometric mean abundance per 10,000 cubic meters trawled at Mossdale. The mean abundance indices varied considerably among years. Sacramento splittail (*Pogonichthys macrolepidotus*) and juvenile Chinook salmon were the most abundant species collected. A very high abundance of Sacramento splittail in 2011 coincided with very high discharge in the San Joaquin River that probably provided a greater extent of spawning habitat; the species responds positively to increased availability of ephemeral habitats with inundated vegetation, such as floodplains (Sommer et al. 1997). Juvenile Chinook salmon mean abundance indices in 2011 and 2012 were appreciably greater than in 2009 and 2010. Threadfin shad (*Dorosoma petenense*) and inland silverside (*Menidia beryllina*) were the third and fourth most abundant small fish collected in the Mossdale trawl, and their mean abundance indices were greatest in 2009. Marked (i.e., adipose-fin-clipped or dyed for gear efficiency studies) juvenile Chinook salmon and striped bass were the only other taxa with mean daily abundance indices greater than 0.1 (Table 2-1).

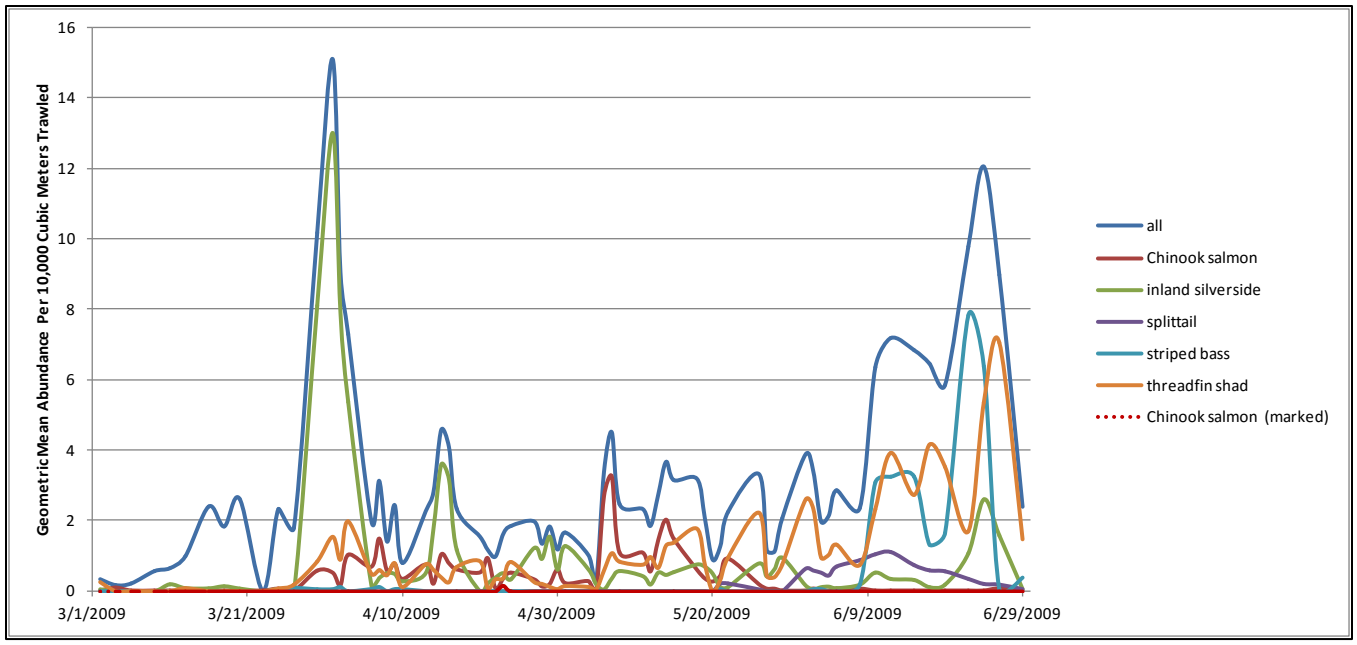
In 2009, high occasional catches of inland silverside occurred from April through June, and a relatively high abundance of threadfin shad and striped bass occurred in June (Figure 2-5). Juvenile Chinook salmon capture occurred from late March to late May, with greatest abundance generally in mid-May. In 2010, peaks in abundance of all fish combined were driven by a number of high catches of splittail from early May to mid-June (Figure 2-6). Catches of juvenile Chinook salmon in 2010 were sporadic, and they were low from early April to early June, but a large peak of marked fish occurred in early June. In 2011, very few fish were collected before late April (Figure 2-7). Subsequently, extremely high catches of splittail occurred in mid- to late May and mid-June, as well as appreciably high catches of juvenile Chinook salmon over the same period. In contrast, very few splittail were collected in 2012, whereas Chinook salmon (marked and unmarked) abundance was by far the highest of all fish, and occurred from early April to early June (Figure 2-8).

Table 2-1
Mean Daily Abundance Index of Fish Species Caught by Mossdale Trawling, Site SAN_1, March–June, 2009–2012

Species	2009	2010	2011	2012	All Years
Sacramento splittail	0.16	2.46	34.52	0.10	10.10
Chinook salmon	0.52	0.23	1.53	1.98	1.10
Threadfin shad	1.22	0.20	0.03	0.03	0.35
Inland silverside	1.09	0.04	0.18	0.10	0.34
Chinook salmon (marked)	0.00	0.25	0.34	0.71	0.33
Striped bass	0.49	0.00	0.00	0.01	0.12
Common carp	0.00	0.00	0.20	0.00	0.06
Goldfish	0.00	0.03	0.10	0.00	0.03
Red shiner	0.04	0.00	0.01	0.07	0.03
Bluegill	0.07	0.01	0.00	0.01	0.02
Largemouth bass	0.00	0.04	0.00	0.01	0.01
Channel catfish	0.01	0.00	0.00	0.03	0.01
Golden shiner	0.02	0.00	0.00	0.01	0.01
White catfish	0.00	0.01	0.00	0.02	0.01
Hardhead	0.00	0.00	0.00	0.03	0.01
Sacramento sucker	0.00	0.00	0.01	0.01	0.01
Pacific lamprey	0.01	0.01	0.00	0.00	0.00
American shad	0.00	0.00	0.00	0.01	0.00
Bass unknown	0.01	0.00	0.00	0.00	0.00
Spotted bass	0.00	0.00	0.00	0.01	0.00
Smallmouth bass	0.00	0.00	0.00	0.00	0.00
Redear sunfish	0.00	0.00	0.00	0.00	0.00
White crappie	0.00	0.00	0.00	0.00	0.00
Black crappie	0.00	0.00	0.00	0.00	0.00
Hitch	0.00	0.00	0.00	0.00	0.00
Tule perch	0.00	0.00	0.00	0.00	0.00
Sacramento pikeminnow	0.00	0.00	0.00	0.00	0.00
Longfin smelt	0.00	0.00	0.00	0.00	0.00
Bigscale logperch	0.00	0.00	0.00	0.00	0.00
Delta smelt	0.00	0.00	0.00	0.00	0.00
Green sunfish	0.00	0.00	0.00	0.00	0.00
Prickly sculpin	0.00	0.00	0.00	0.00	0.00
Wakasagi	0.00	0.00	0.00	0.00	0.00
Lamprey unknown	0.00	0.00	0.00	0.00	0.00
Shimofuri goby	0.00	0.00	0.00	0.00	0.00
Sacramento blackfish	0.00	0.00	0.00	0.00	0.00

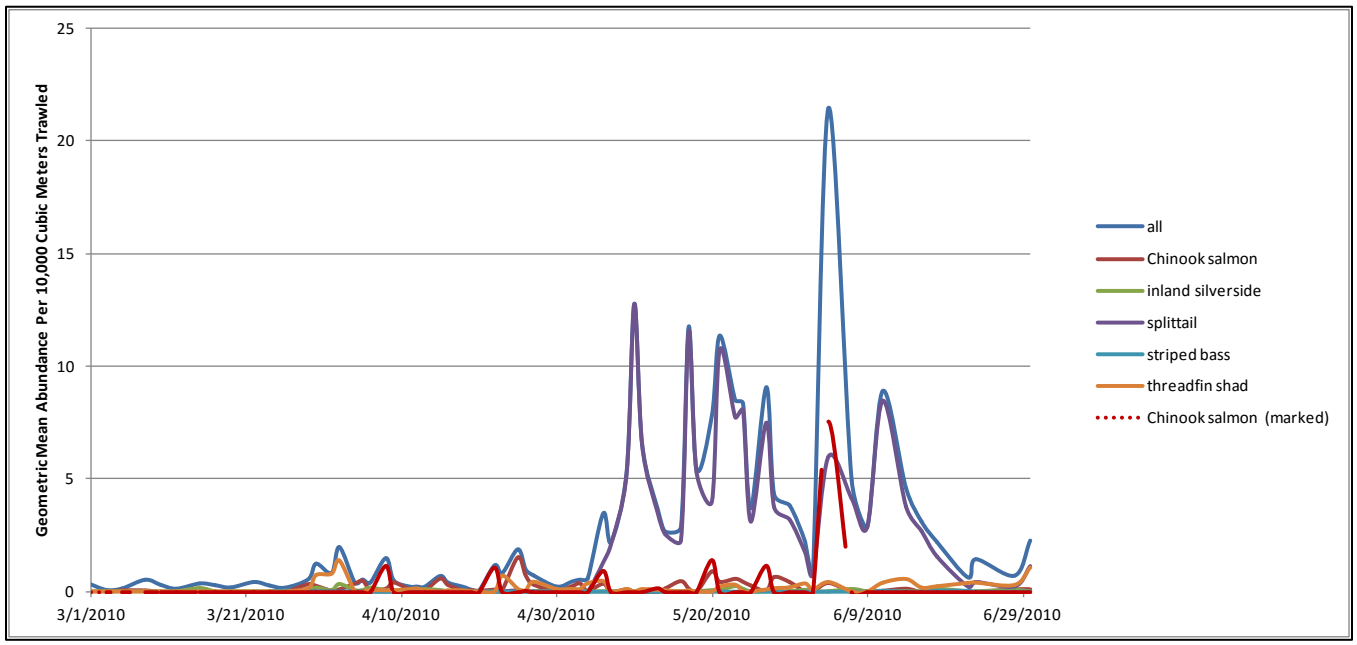
Note: Abundance index = geometric mean number of fish per 10,000 cubic meters trawled each day (typical sampling effort = 10 trawls per day).

Source: Compiled from data provided by Speegle, pers. comm., 2011–2012



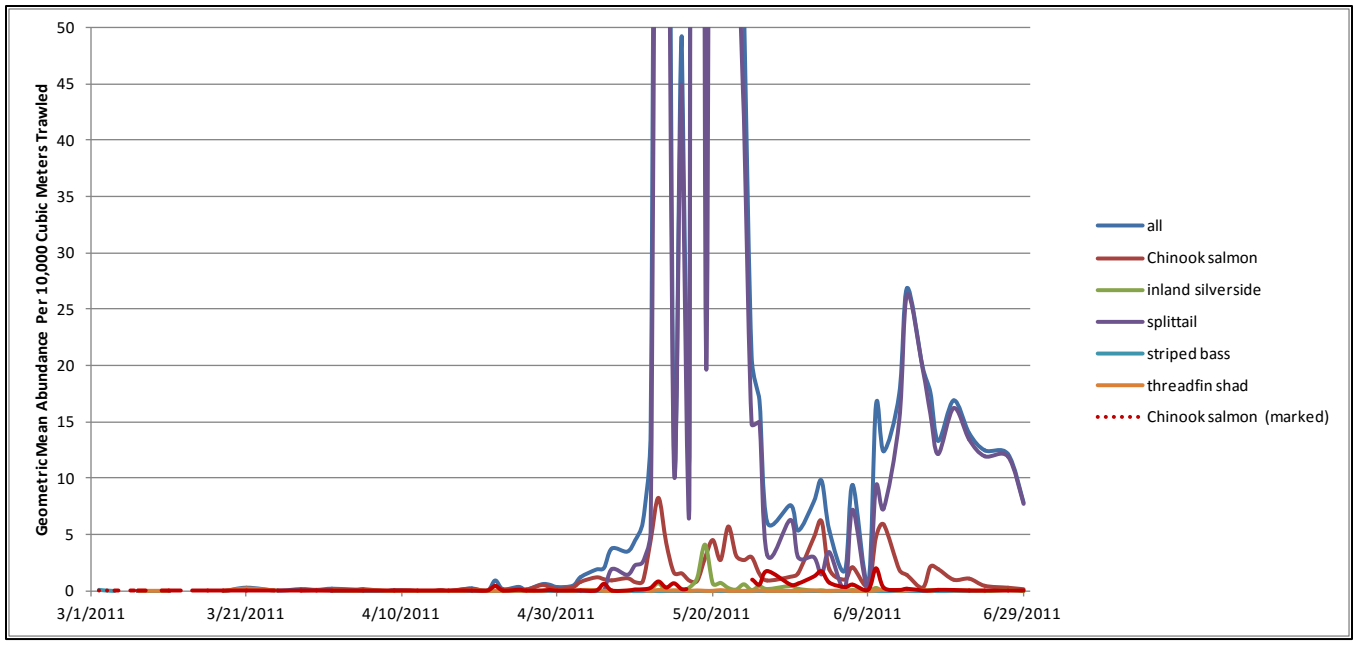
Source: Compiled from data provided by Speegle, pers. comm., 2011–2012

Figure 2-5 **Common Fish Species Geometric Mean Abundance per 10,000 Cubic Meters from Mossdale Trawling, Site SAN_1, March–June 2009**



Source: Compiled from data provided by Speegle, pers. comm., 2011–2012

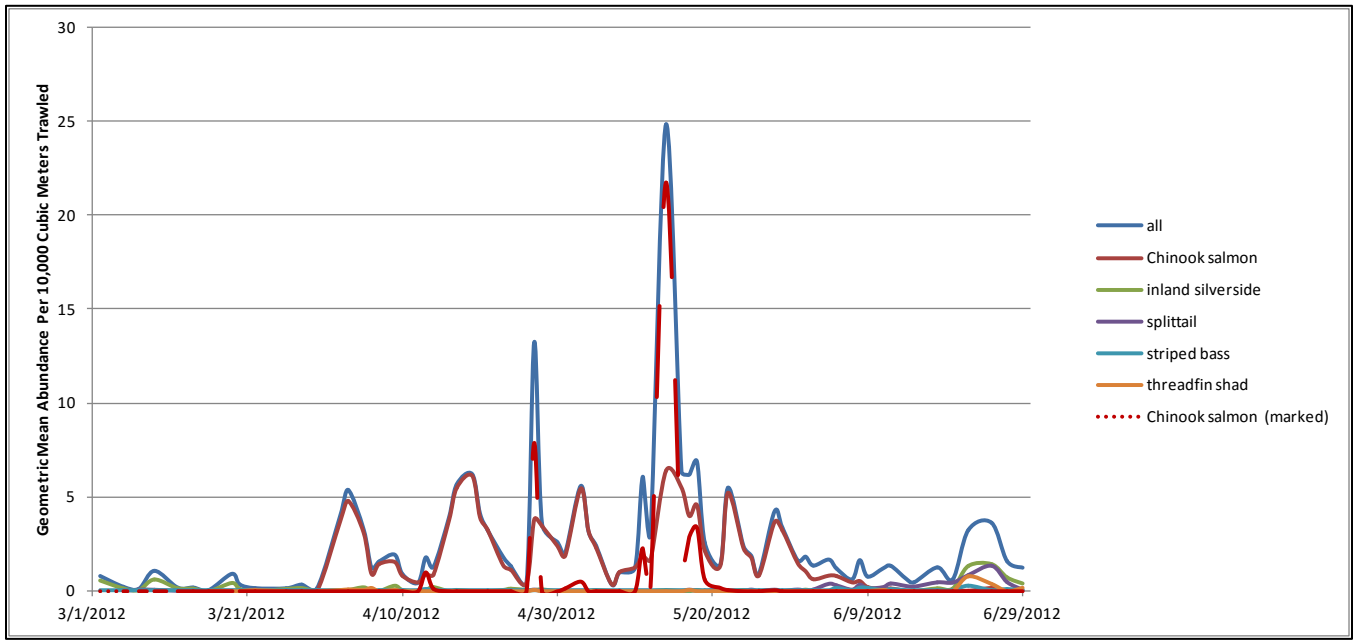
Figure 2-6 **Common Fish Species Geometric Mean Abundance per 10,000 Cubic Meters from Mossdale Trawling, Site SAN_1, March–June 2010**



Note: Y-axis is truncated; maximum abundance was greater than 600.

Source: Compiled from data provided by Speegle, pers. comm., 2011–2012

Figure 2-7 **Common Fish Species Geometric Mean Abundance per 10,000 Cubic Meters from Mossdale Trawling, Site SAN_1, March–June 2011**



Source: Compiled from data provided by Speegle, pers. comm., 2011–2012

Figure 2-8 **Common Fish Species Geometric Mean Abundance per 10,000 Cubic Meters from Mossdale Trawling, Site SAN_01, March–June 2011**

NEARSHORE (SEINING AND ELECTROFISHING)

Seining at three stations in the general vicinity of the HOR study area from March through June, 2009 through 2012, collected 25 fish taxa of less than 150 mm FL, of which nine were native (Table 2-2). The introduced species inland silverside and red shiner (*Cyprinella lutrensis*) dominated the catch (approximately 70% of all fish collected), with two native species (Sacramento sucker [*Catostomus occidentalis*] and splittail) constituting nearly 18% of all fish collected.

Table 2-2
Number of Fish Collected at San Joaquin River Beach Seining Stations SJ051E, SJ056E, SJ058W, March–June, 2009–2012

Species	2009	2010	2011	2012	All Years
Inland silverside	746	708	365	336	2155
Red shiner	442	750	301	273	1766
Sacramento sucker	54	194	74	232	554
Sacramento splittail	6	206	230	2	444
Largemouth bass	18	20	17	57	112
Bluegill	26	37	6	41	110
Threadfin shad	58	8	0	6	72
Prickly sculpin	0	1	6	52	59
Common carp	0	2	52	2	56
Western mosquitofish	15	19	7	3	44
Black crappie	1	0	0	36	37
Golden shiner	5	6	8	14	33
Chinook salmon	0	7	14	10	31
Redear sunfish	6	3	0	10	19
Sacramento pikeminnow	0	13	3	0	16
Striped bass	7	2	0	6	15
Tule perch	2	1	0	11	14
Chinook salmon (marked)	0	0	9	2	11
Bigscale logperch	0	2	0	7	9
Yellowfin goby	8	0	0	0	8
Spotted bass	0	1	1	4	6
Fathead minnow	1	0	4	0	5
Pacific staghorn sculpin	0	0	0	3	3
American shad	0	0	0	2	2
Hardhead	0	0	1	0	1
Sacramento blackfish	0	0	0	1	1

Source: Speegle, pers. comm., 2011–2012

Thirteen fish species were collected during four electrofishing samples in the San Joaquin River downstream from the HOR study area in April and June 2009 and 2010 (Table 2-3). The most abundant fish collected were bluegill (*Lepomis macrochirus*) (35% of total catch), white catfish (18%), threadfin shad (9%), and striped bass (8%). Native fish (Sacramento sucker and prickly sculpin [*Cottus asper*]) made up only 3% of the total catch. Of the four focal predatory fish species from the present study, white catfish (68–301 mm FL) were most abundant, followed by striped bass (115–459 mm FL), largemouth bass (160–385 mm FL; 7% of total catch), and channel catfish (199–447 mm FL; 5% of total catch). Other potential predatory fish collected during electrofishing (smallmouth bass [*Micropterus dolomieu*] and prickly sculpin) were a very minor part of the catch (Table 2-3).

Table 2-3
Number and Size of Fish Collected By Electrofishing in the San Joaquin River Downstream from the HOR Study Area, April and June, 2009–2010

Species	Number					Fork Length (mm)		
	4/21/2009	6/17/2009	4/15/2010	6/23/2010	Total	Min.	Mean	Max.
Bluegill	9	48	8	27	92	52	133.0	231
White catfish	20	6	6	15	47	68	246.0	301
Threadfin shad	0	20	1	4	25	84	100.1	126
Striped bass	9	6	2	3	20	115	190.8	459
Largemouth bass	3	3	8	4	18	160	262.5	385
Redear sunfish	4	9	1	4	18	44	178.8	293
Channel catfish	7	3	0	3	13	199	334.3	447
Common carp	4	0	2	4	10	NA	NA	NA
Green sunfish	3	1	1	1	6	119	146.8	171
Inland silverside	3	2	1	0	6	71	80.3	95
Sacramento sucker	1	0	4	1	6	428	466.8	510
Spotted bass	1	1	0	0	2	190	195.5	201
Prickly sculpin	1	0	0	0	1	128	128.0	128

Notes: HOR = Head of Old River; mm = millimeters
Data are for site SAN_1 (UTM Zone 10 N, Northing: 4187551.004; Easting: 648320.84).
Source: Conrad, pers. comm., 2013

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3 PHYSICAL PARAMETERS

Data summarized in this chapter for physical parameters during the 2009 through 2012 study years were from local monitoring stations and generally consisted of 15-minute observations (discharge, water temperature, and turbidity). These data were from the California Data Exchange Center (CDEC) (Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013). In addition, water velocity data were modeled, as described herein.

3.1 DISCHARGE AND TIDAL REGIME

3.1.1 2009 DISCHARGE

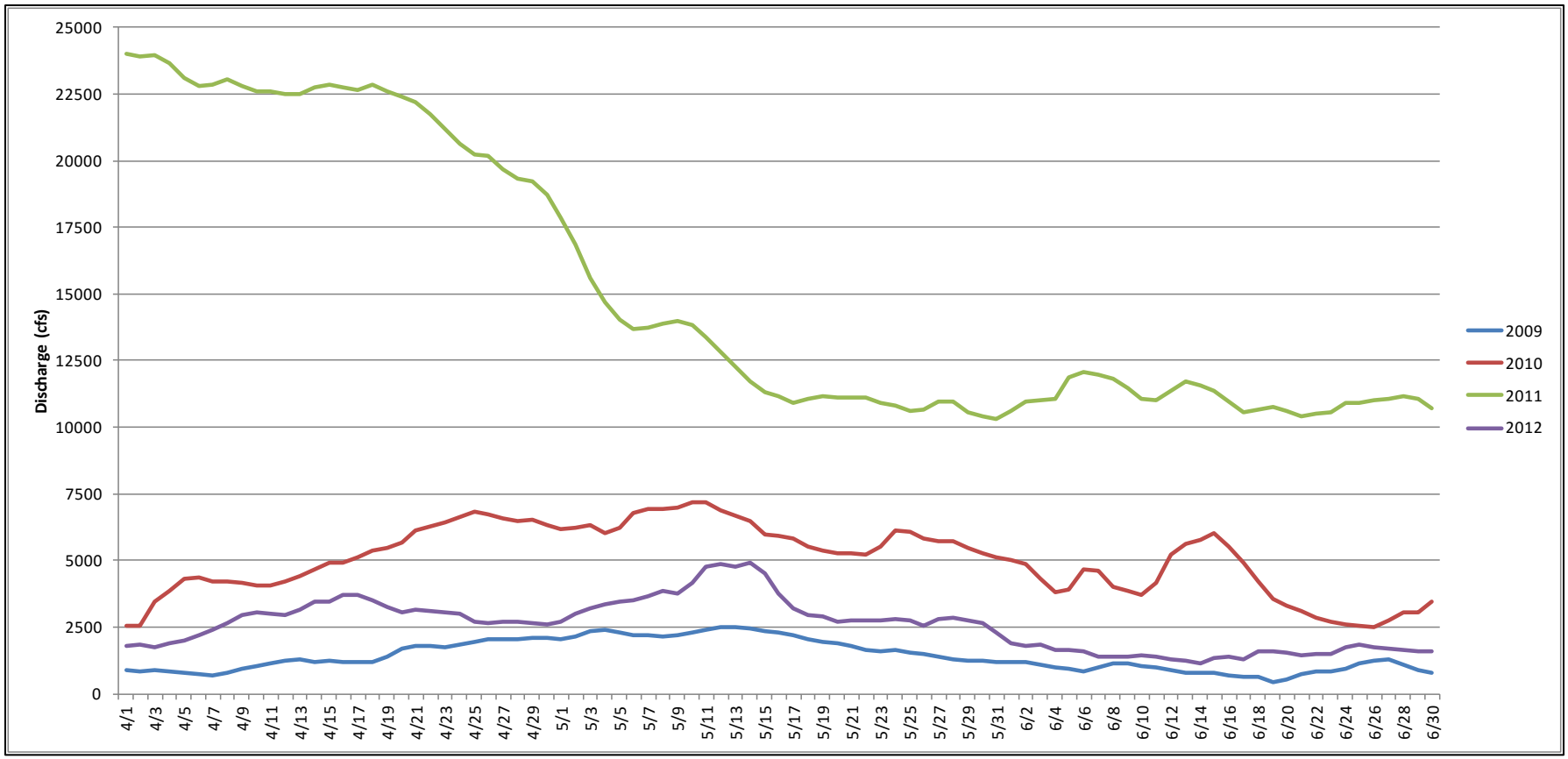
Within the study area, discharge from April through June 2009 was the lowest during the 4-year study period (Figure 3-1). The official water year classifications based on May 1 runoff forecasts were dry in 2009 and 2012, above normal in 2010, and wet in 2011 (State of California 2013). In 2009, low discharge in the San Joaquin River at Mossdale (MSD) led to frequent flow reversals at that location, and the San Joaquin River at Lathrop (SJL), just downstream of the HOR study area, was close to fully tidal much of the time (Figure 3-2). Ebb tide discharge rarely exceeded 2,000 cubic feet per second (cfs) at SJL, and flood tide discharge was nearly as low at -2,000 cfs. SJL flows during the period in which tagged juvenile Chinook salmon arrived into the HOR study area generally were within the range of -1,000 to 2,000 cfs (Figure 3-2).

The division of discharge at the HOR between Old and San Joaquin rivers is of considerable relevance to the analyses of barrier effectiveness described later in this chapter. Estimates of the proportion of discharge entering Old River tend to be extremely variable when made at the 15-minute scale, so summaries were created by calculating daily sums of 15-minute readings of discharge at the Old River at Head (OH1) and dividing by the corresponding daily sums of 15-minute San Joaquin River at Mossdale (MSD) discharge. From April through June 2009, daily discharge at OH1 averaged 0.81 (81%) of daily discharge at Mossdale (range: 0.60 to 1.18), suggesting that the great majority of discharge had entered Old River during this time (Figure 3-3). During the period from April 23 through May 18 in which tagged juvenile Chinook salmon arrived at the HOR study area, daily discharge at OH1 averaged 0.65 of the daily discharge at MSD (range 0.60 to 0.73) (Table 3-1).

3.1.2 2010 DISCHARGE

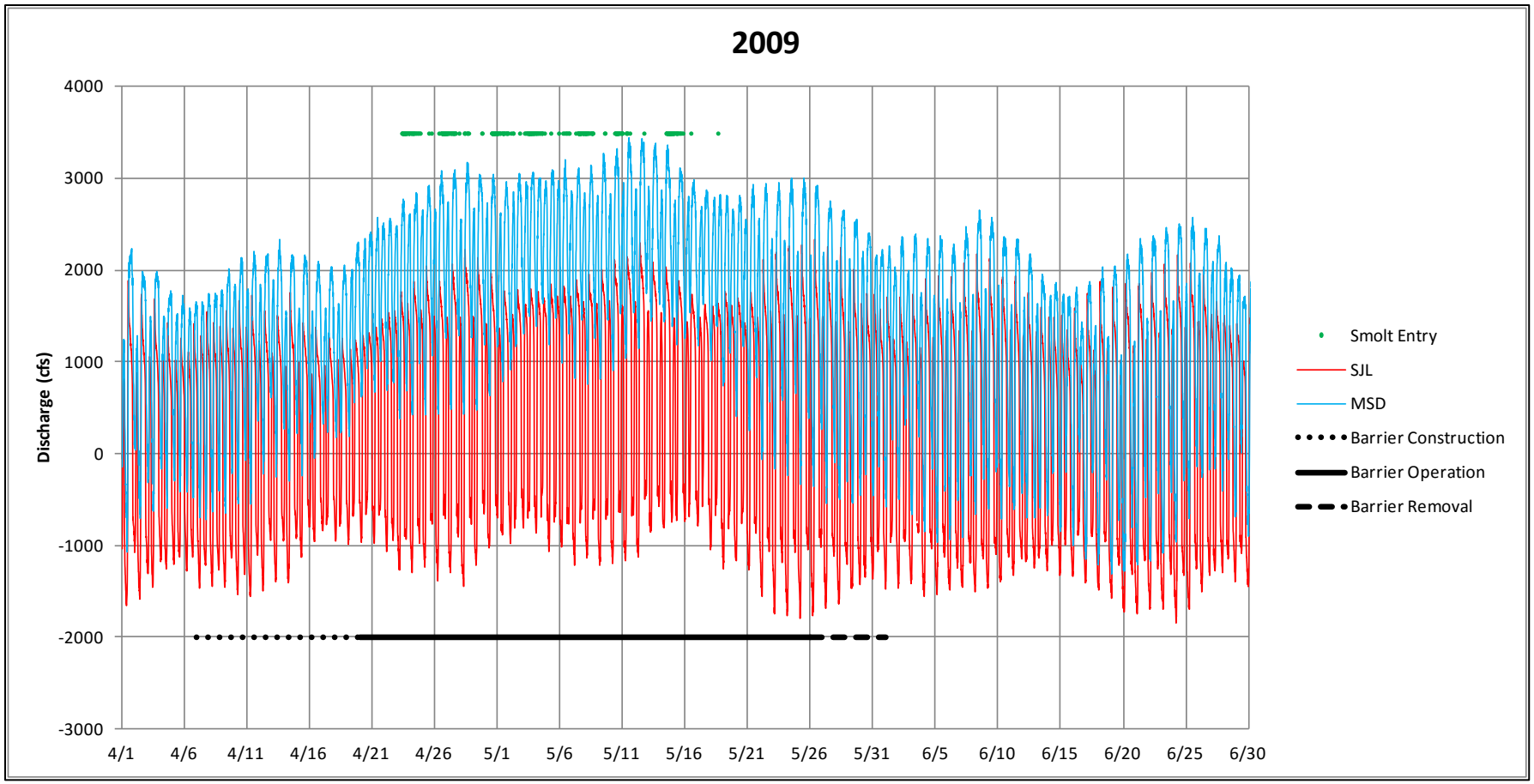
The April through June discharge in 2010 was appreciably higher than in 2009 (Figure 3-1), with the MSD discharge varying between a low of approximately 650 cfs in early April and a high of nearly 7,900 cfs during the period of tagged juvenile Chinook salmon entry in May (Figure 3-4). The SJL discharge exhibited tidal reversals in April, late May, and June, but during the period of juvenile entry, discharge was higher and generally ranged from 1,000 cfs to 3,000 cfs.

From April through June 2010, daily discharge at OH1 averaged 0.54 (54%) of daily discharge at MSD (range: 0.43 to 0.80), suggesting that just more than one-half of discharge had entered Old River during this time (Figure 3-3). During the period from April 27 through May 20, in which tagged juvenile Chinook salmon entered the area, daily discharge at OH1 averaged 0.44 of the daily discharge at MSD (range 0.43 to 0.45) (Table 3-1).



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

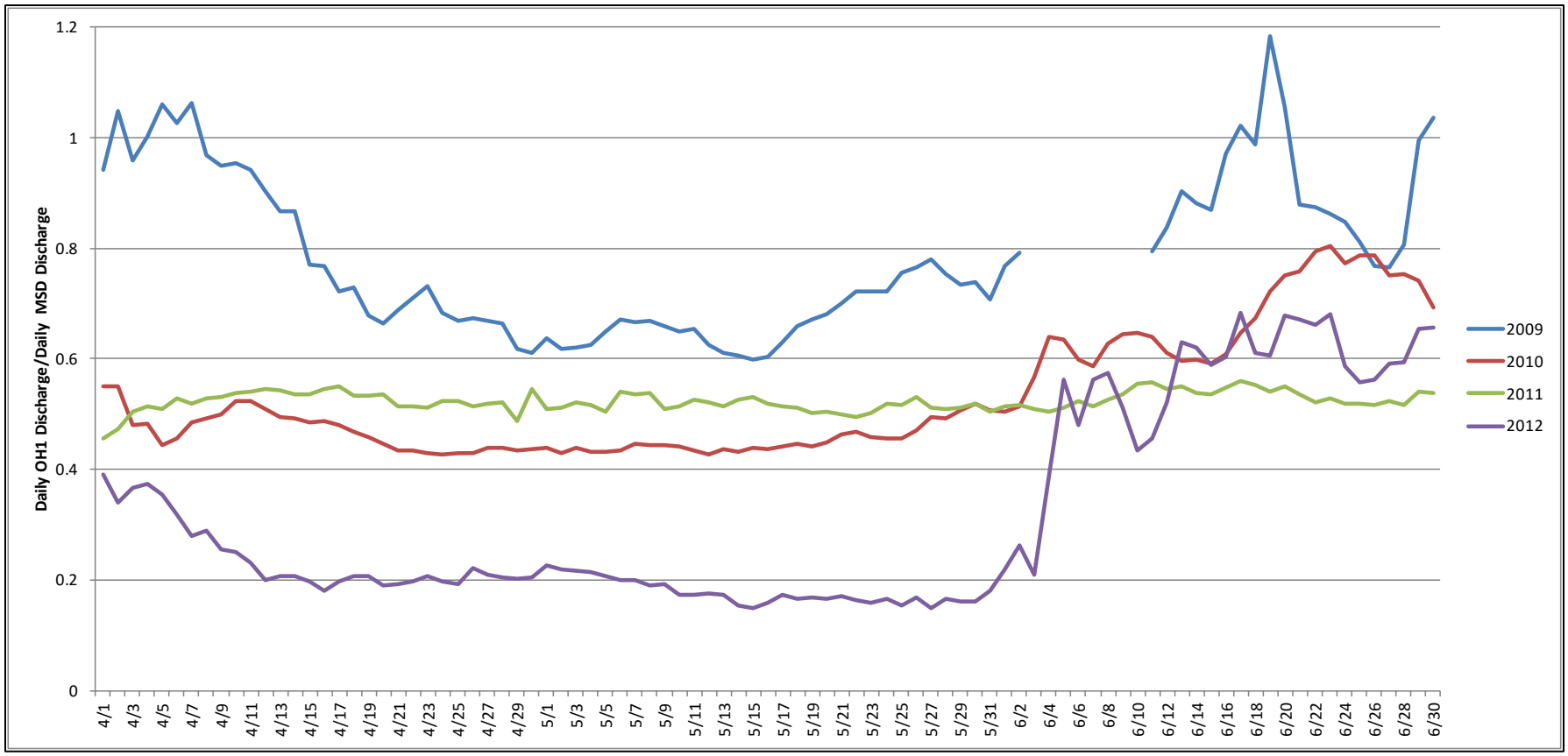
Figure 3-1 **Daily Mean River Discharge in the San Joaquin River at Mossdale (MSD), 4/1 through 6/30, 2009–2012**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

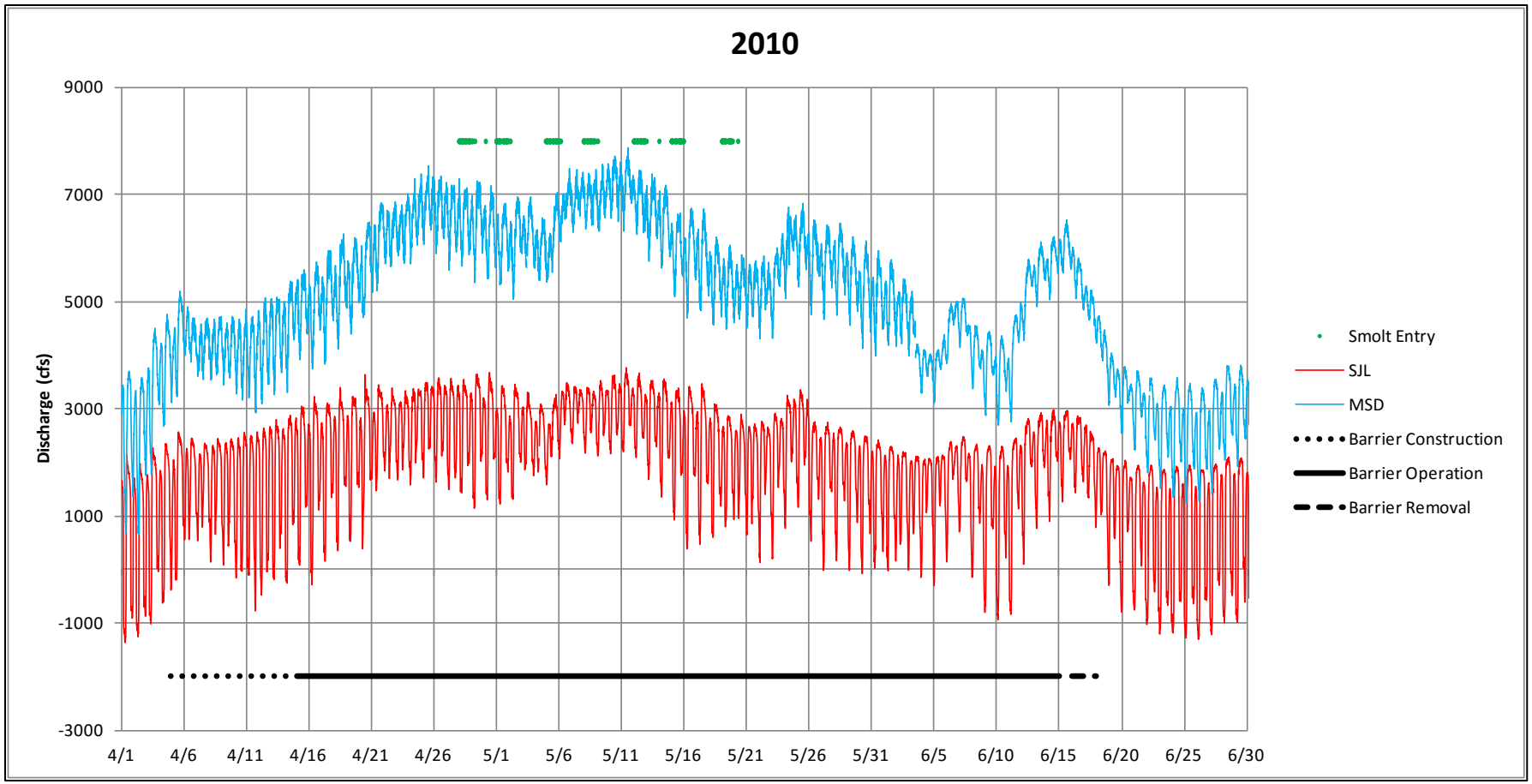
Note: The barrier referred to in the legend was a non-physical fish barrier called a BAFF (Fish Guidance Systems Ltd., Southampton, UK). Barrier operation was not continuous, with the BAFF off approximately 50% of the time during the period of BAFF operation.

Figure 3-2 **15-Minute River Discharge in the San Joaquin River at Mossdale (MSD) and Lathrop (SJL), 4/1/09 through 6/30/09, in Relation to Acoustically Tagged Juvenile Chinook Salmon Arrival into the Head of Old River Study Area (Green Dots)and Non-physical Barrier Construction/Operation/Removal (Black Lines)**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Figure 3-3 **Old River Head (OH1) Daily Discharge as a Proportion of San Joaquin River at Mossdale, Daily Discharge, April-June, 2009-2013**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: The barrier referred to in the legend was a non-physical fish barrier called a BAFF (Fish Guidance Systems Ltd., Southampton, UK). Barrier operation was not continuous with the BAFF off approximately 50% of the time during the period of BAFF operation.

Figure 3-4 **15-Minute River Discharge in the San Joaquin River at Mossdale (MSD) and Lathrop (SJL), 4/1/10 through 6/30/10, in Relation to Acoustically Tagged Juvenile Chinook Salmon Entry into the Head of Old River Study Area (Green Dots)and Non-physical Barrier Status (Black Lines)**

Table 3-1
Descriptive Statistics for 2009–2012 HOR Average Daily Discharge as Proportion of San Joaquin River at Mossdale Average Daily Discharge during Periods when Tagged Juvenile Chinook Salmon Arrived at the HOR Study Area

			Daily OH1 Discharge/Daily MSD Discharge				
Year	First Fish[1]	Last Fish[2]	Mean	Standard Deviation	Minimum	Maximum	Count
2009	4/23/09; 8:24	5/18/09; 13:48	0.65	0.03	0.60	0.73	26
2010	4/27/10; 22:25	5/20/10; 5:54	0.44	0.01	0.43	0.45	24
2011	5/4/11; 2:51	6/22/11; 4:24	0.52	0.02	0.49	0.56	50
2012	4/28/12; 4:13	5/29/12; 16:35	0.18	0.02	0.15	0.23	32

Notes: HOR = Head of River; OH1 = Old River at Head; MSD = San Joaquin River at Mossdale
The OH1 gauge is 0.25 km downstream of the HOR site; the MSD gauge is ~4.5 km upstream of the HOR site. The periods reported here are based on values observed during the period between first and last detections of fish.

[1] Date/time when the first tagged salmonids was nearest the BAFF line.

[2] Date/time the last tagged salmonids was nearest the BAFF line.

[3] SJR Flow Proportion = 1 - (Mean of (Daily OH1 Discharge/Daily MSD Discharge)); therefore SJR Flow Proportion = 0.35 (2009), 0.56 (2010), 0.48 (2011), and 0.82 (2012).

Source: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

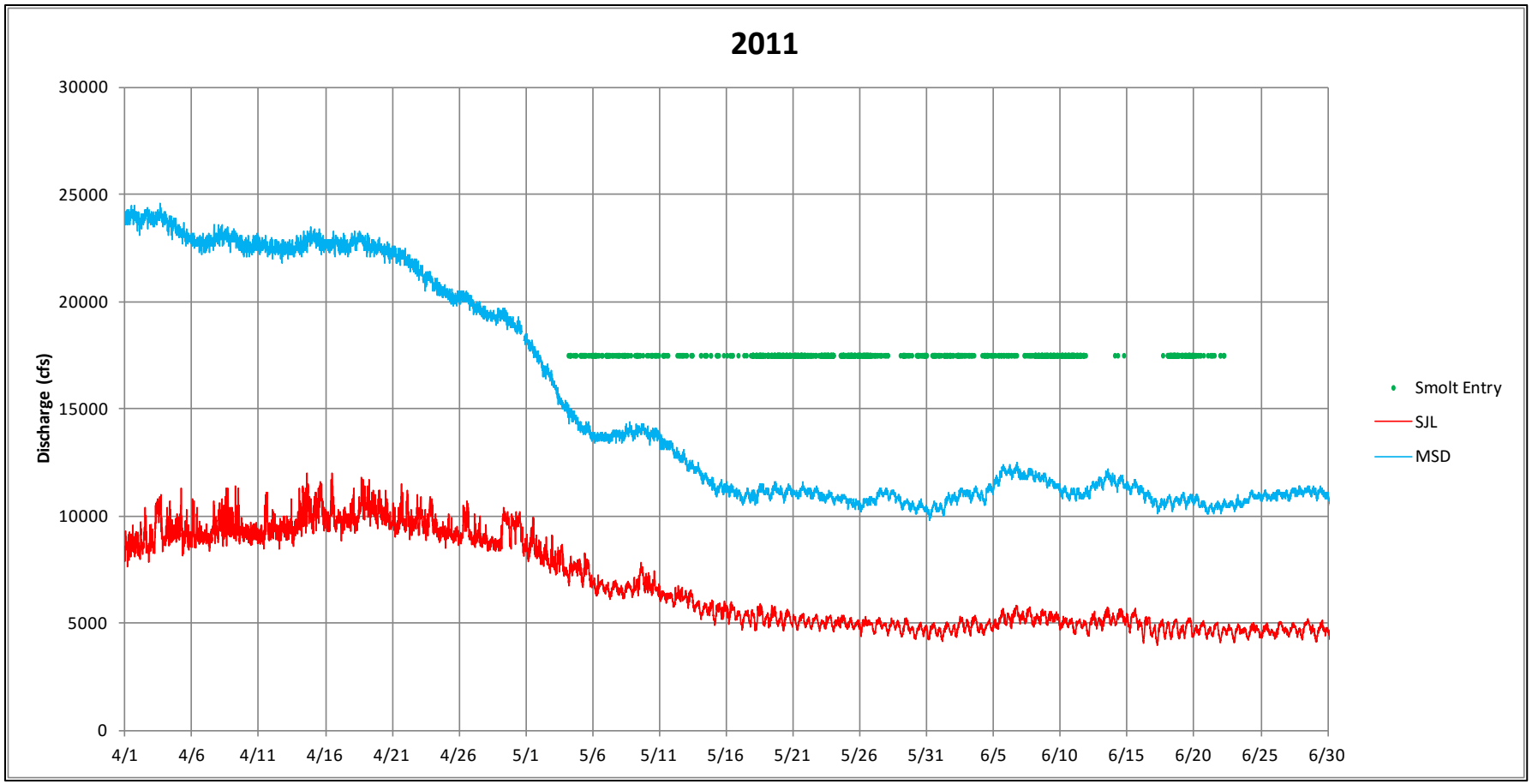
3.1.3 2011 DISCHARGE

Discharge from April through June 2011 was exceptionally high as a result of unseasonably high precipitation (Figure 3-1). Discharge at MSD exceeded 24,000 cfs in early April and remained higher than 10,000 cfs for most the entire 3-month period (Figure 3-5). The discharge at the SJL gauge was higher than 10,000 cfs during much of April, and was approximately 7,500 cfs at the beginning of tagged juvenile salmonid entry into the HOR study area in early May, before decreasing to approximately 5,000 cfs from approximately mid-May thru the end of June. The tidal signal was appreciably muted in 2011 because of the high river discharge.

From April through June 2011, daily discharge at OH1 averaged 0.51 (51%) of daily discharge at MSD (range: 0.44 to 0.90), suggesting that approximately one-half of the discharge had entered Old River during this time (Figure 3-3). During the period from May 5 through June 22, in which tagged juvenile salmonids entered the area, daily discharge at OH1 averaged 0.52 of the daily discharge at MSD (range 0.49 to 0.56) (Table 3-1).

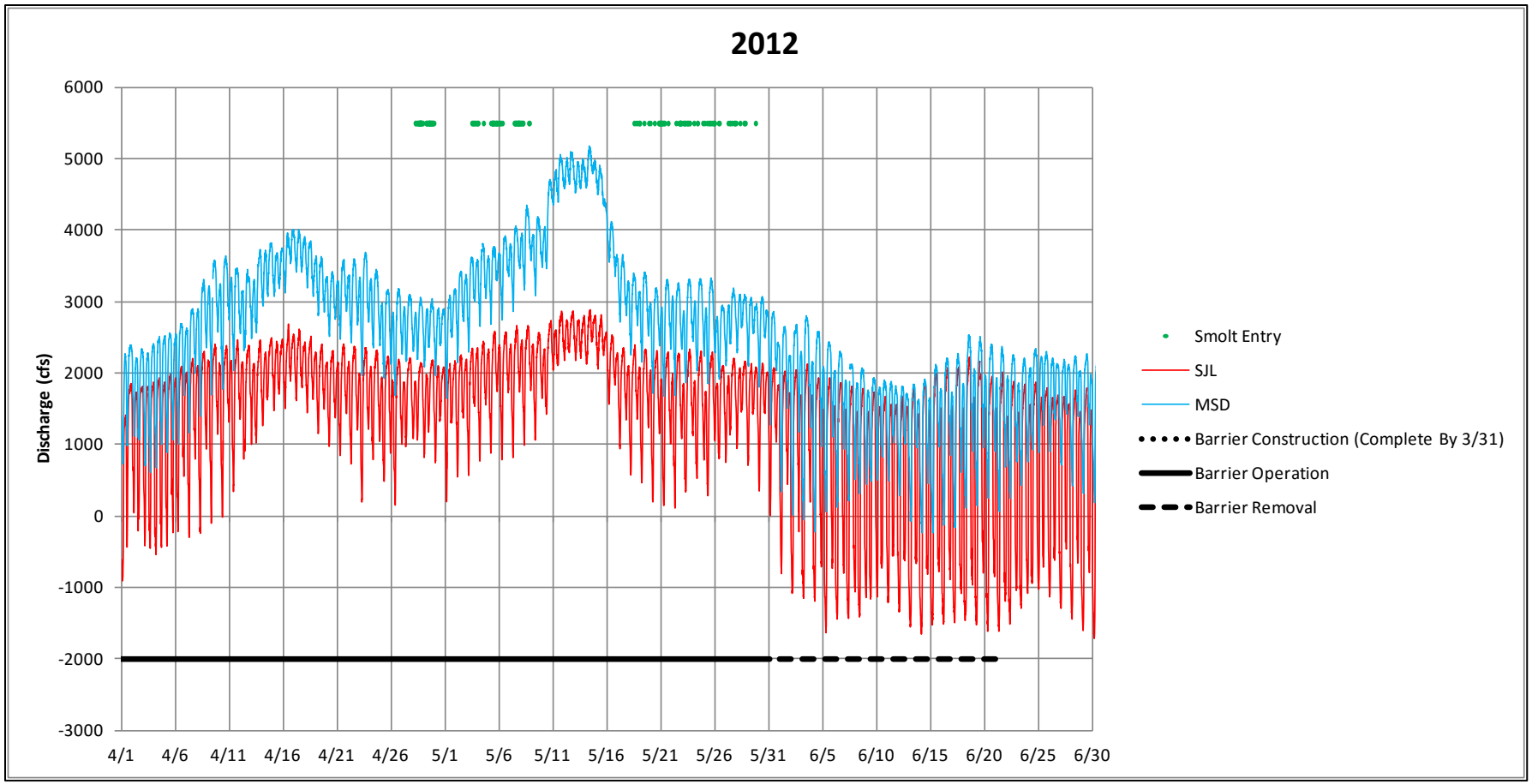
3.1.4 2012 DISCHARGE

Discharge in 2012 from April through June was greater than in 2009, but less than 2010 (Figure 3-1). Tidal flow reversals occurred at SJL in April and June, with a handful of reversals at MSD in June (Figure 3-6). The SJL discharge during the period of tagged juvenile salmonid entry to the HOR study area generally varied from more than 1,000 to 2,500 cfs in late April/early May, and from less than 1,000 cfs to just more than 2,000 cfs from mid- to late June. No juveniles entered the area during elevated discharge of approximately 4,500 to 5,000 cfs at MSD from May 10 through 15 (Figure 3-6).



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Figure 3-5 **15-Minute River Discharge in the San Joaquin River at Mossdale (MSD) and Lathrop (SJL), 4/1/11 through 6/30/11, in Relation to Acoustically Tagged Juvenile Chinook Salmon and Steelhead Arrival into the Head of Old River Study Area (Green Dots)**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: The barrier referred to in the legend was a rock barrier with eight culverts.

Figure 3-6 **15-Minute River Discharge in the San Joaquin River at Mossdale (MSD) and Lathrop (SJL), 4/1/12 through 6/30/12, in Relation to Acoustically Tagged Juvenile Chinook Salmon Entry into the Head of Old River Study Area (Green Dots) and Rock Barrier Status (Black Lines)**

From April through June 2012, daily discharge at OH1 averaged 0.44 (44%) of daily discharge at MSD (range: 0.15 to 1.05), suggesting that just less than one-half of the discharge had entered Old River during this time interval (Figure 3-3). During the period from April 28 through May 29, in which tagged juvenile salmonids entered the area, daily discharge at OH1 averaged 0.18 of the daily discharge at MSD (range 0.15 to 0.23) (Table 3-1). This relatively low proportion of discharge reflected the installation of the rock barrier that occurred from April 1 through May 31 (Figure 3-6), and represents the discharge either passing through the barrier's culverts or between the rocks that made up the barrier.

3.2 VELOCITY FIELD

Hydrodynamic data were collected in 2009, 2011, and 2012 to provide information on the velocity field at the HOR study area. These data sets provide a three-dimensional (3D) water velocity field at discrete time periods.

3.2.1 METHODS

In 2009 and 2011, hydrodynamic data were collected using a downward-looking acoustic Doppler current profiler (DL-ADCP) from a moving boat. Measurements were taken on February 2, March 3 and 13, May 29, and June 5, 2009, and on April 12, 2011. In 2012, near-surface hydrodynamic data were collected using side-looking (SL) ADCPs, deployed near the bank and profiling across the river at four locations for the duration of the study period, April 23 through May 30. The SL-ADCP data were interpolated to generate a near-surface 2D velocity field. On May 8 and 30, 2012, DL-ADCP measurements were taken to validate the 2D velocity interpolation.

DL-ADCP DATA PROCESSING AND INTERPOLATION

The DL-ADCP measurements were made synoptically during the same time intervals for 8 days in each year (i.e., 2009, 2011, and 2012). The processing methods included correcting Differential Global Positioning System (DGPS) tracks, objectively filtering out suspect data, spatially smoothing based on a 3-point weighted average, and extrapolating velocity vectors to the bed (bottom substrate) (Dinehart and Burau 2005). The processed DL-ADCP measurements were interpolated to produce a 3D velocity field for each time interval in 2009, 2011, and 2012. The 3D interpolated velocity fields were generated using an algorithm that releases particles into the initial velocity field and interpolates velocities along the particle pathlines, using an inverse path length weighting (IPLW) function. This algorithm iterates until the changes in the velocity field are minimal.

SL-ADCP DATA PROCESSING AND INTERPOLATION

The SL-ADCP measurements were made continuously at 15-minute intervals from April 23 through May 30, 2012, except for an 18-hour period from April 29 through April 30 and a 27-hour period from May 5 through May 7 due to a technical malfunction that resulted in recording erroneous data. The data processing included merging the SL-ADCP data into a single file, geo-referencing the measurement locations, conducting visual quality assurance/quality control checks, and estimating (when possible) data gaps. The 2D interpolated velocity fields were generated for a 5-meter by 5-meter set of grid points every 15 minutes using an algorithm that releases particles into the processed velocity field and interpolates velocities along the particle pathlines using an IPLW function. This algorithm iterates until the changes in the mean velocity field are minimal.

3.2.2 RESULTS

Near-surface 2D velocity fields from the DL-ADCP and SL-ADCP data (hereafter referred to as DL2D and SL2D) were used to examine velocity fields and hydrodynamic features over a range of river discharges (Table 3-2). The discharge values (SJL) were chosen to represent reverse and typical flows from 2009; very high flows from 2011; and the 5th, 25th, 50th, 75th, and 95th percentile flows from 2012.

Table 3-2
Summary of Velocity Fields Generated from DL-ADCP Data in 2009 and 2011, and SL-ADCP Data from 2012

Discharge at San Joaquin near Lathrop (cfs)	-1,360	780	1,450	1,500	1,970	2,000	2,250	2,660	9,535
Timestamp (PST)	5/29/2009 09:25	2012[1]	6/05/2009 10:00	2012[1]	2012[1]	2012[1]	2012[1]	2012[1]	04/12/2011 10:10
Rationale	Negative-flow condition (common occurrence in 2009)	5th percentile of 2012 flows	Common low-flow condition in 2009 (and 2010)	25th percentile of 2012 flows	50th percentile of 2012 flows	Intermediate discharge of interest	75th percentile of 2012 flows	95th percentile of 2012 flows	High-flow condition observed only in 2011

Notes: cfs = cubic feet per second; DL-ADCP = downward-looking acoustic Doppler current profiler; PST = Pacific Standard Time; SL-ADCP = side-looking acoustic Doppler current profiler

[1] Multiple instances for specified discharge value.

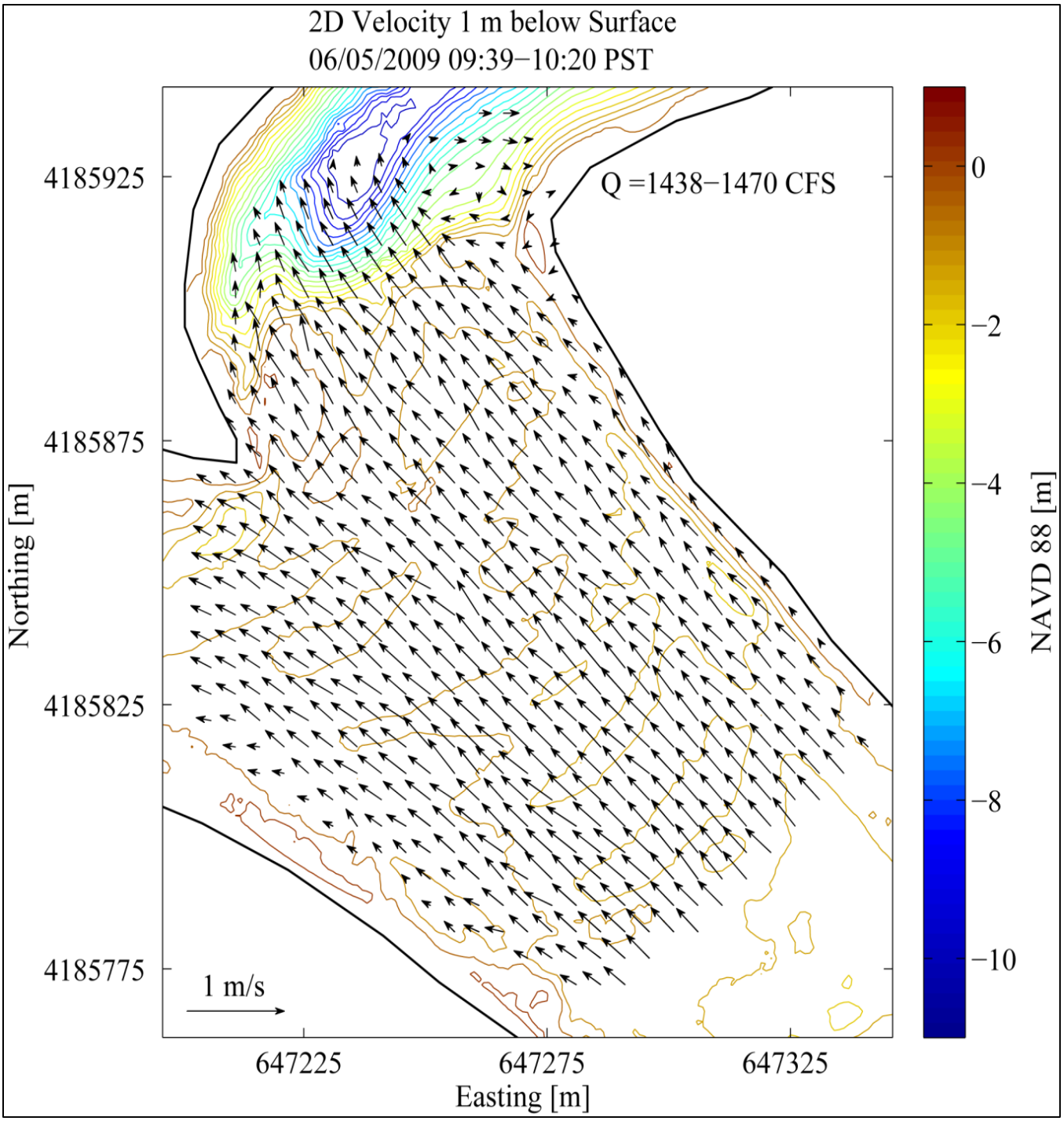
Source: Present study

VELOCITY MODELING OF 2009 AND 2011 (NO ROCK BARRIER)

Data from 2009 and 2011 provided information on the HOR velocity field in the absence of a physical barrier. At a SJL discharge of approximately 1,450 cfs, a commonly observed discharge in 2009, near-surface velocity was primarily in a downstream direction and was greatest in the mid-channel San Joaquin River, close to the divergence with Old River (Figure 3-7).

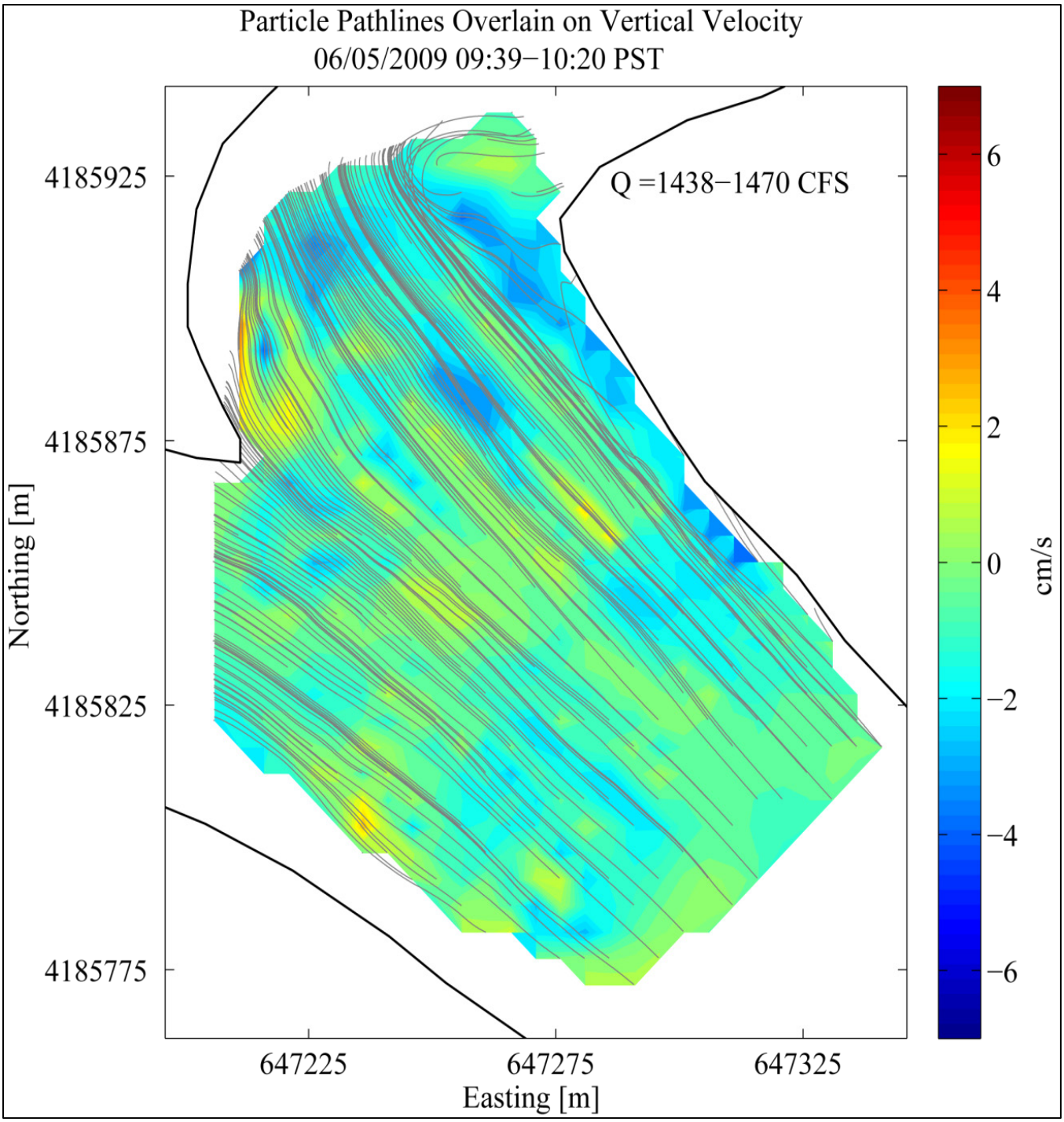
An eddy formed near a sand spit on the right bank of the San Joaquin River east of the deepest part of the scour hole (Figure 3-8). Vertical velocity primarily was downward at around 0 to 2 centimeters per second (cm/s). With reverse flows of approximately -1,360 cfs in 2009, a large eddy and related irregular velocities occurred on the right side of the San Joaquin River upstream of the divergence with Old River (Figures 3-9 and 3-10). Upstream velocity was of relatively high magnitude (approximately 0.33 m/s at discharge of approximately -1,300 to -1,450 cfs) (see Figure 3-9) on the left side of the San Joaquin River closest to the divergence with Old River. A low-velocity eddy also was apparent at the scour hole. Vertical velocity was primarily upward near the scour hole and mostly downward elsewhere.

Very high discharge in 2011 resulted in a downstream velocity of appreciable magnitude (e.g., >≥1 m/s) (Figure 3-11). Vertical velocity during this time was primarily downward, at more than 6 cm/s in many areas (Figures 3-7 through 3-12).



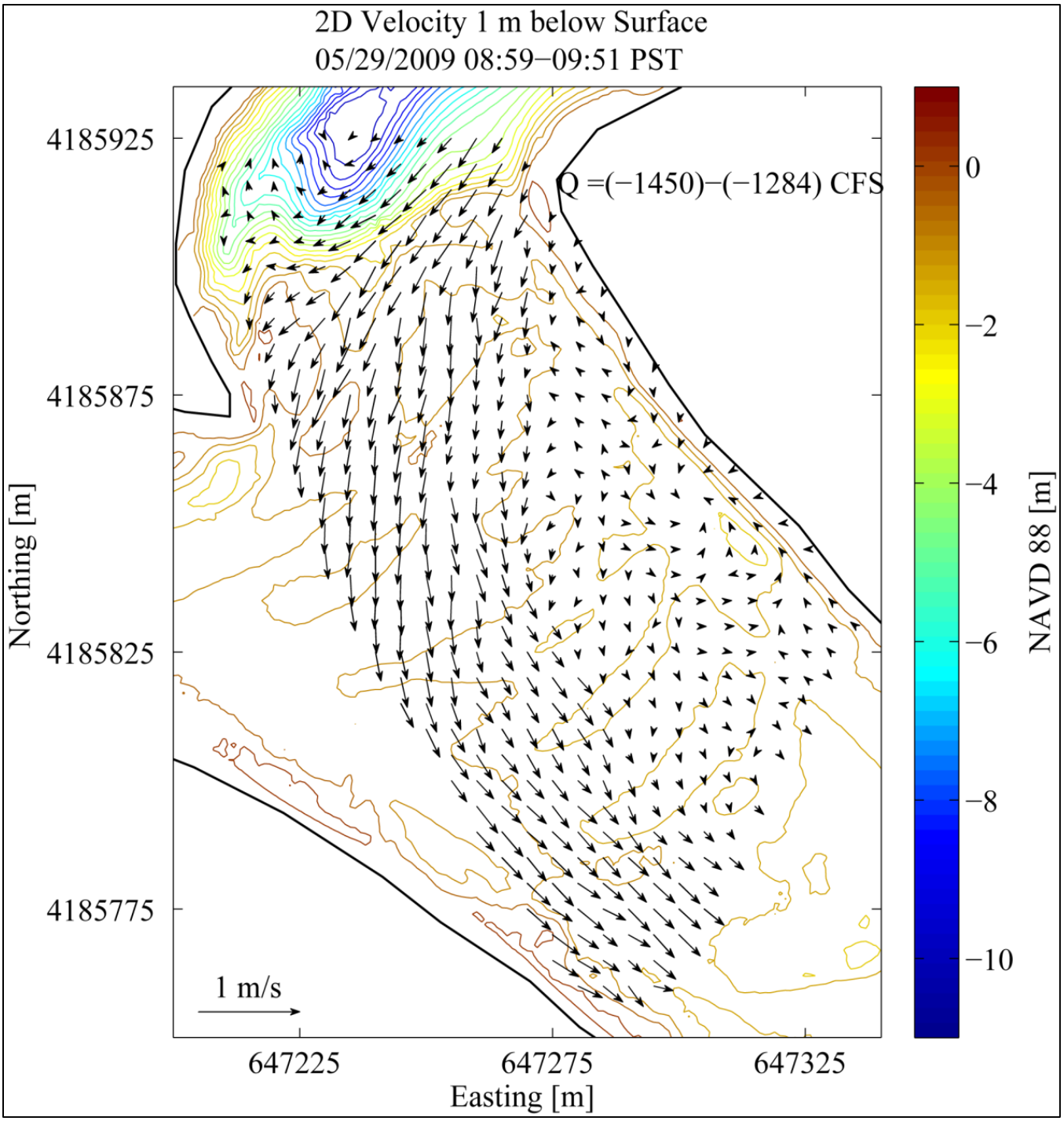
Source: Present study

Figure 3-7 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a DL-ADCP at the Head of Old River, 6/5/2009, 0939–1020 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 1,438 to 1,470 cfs**



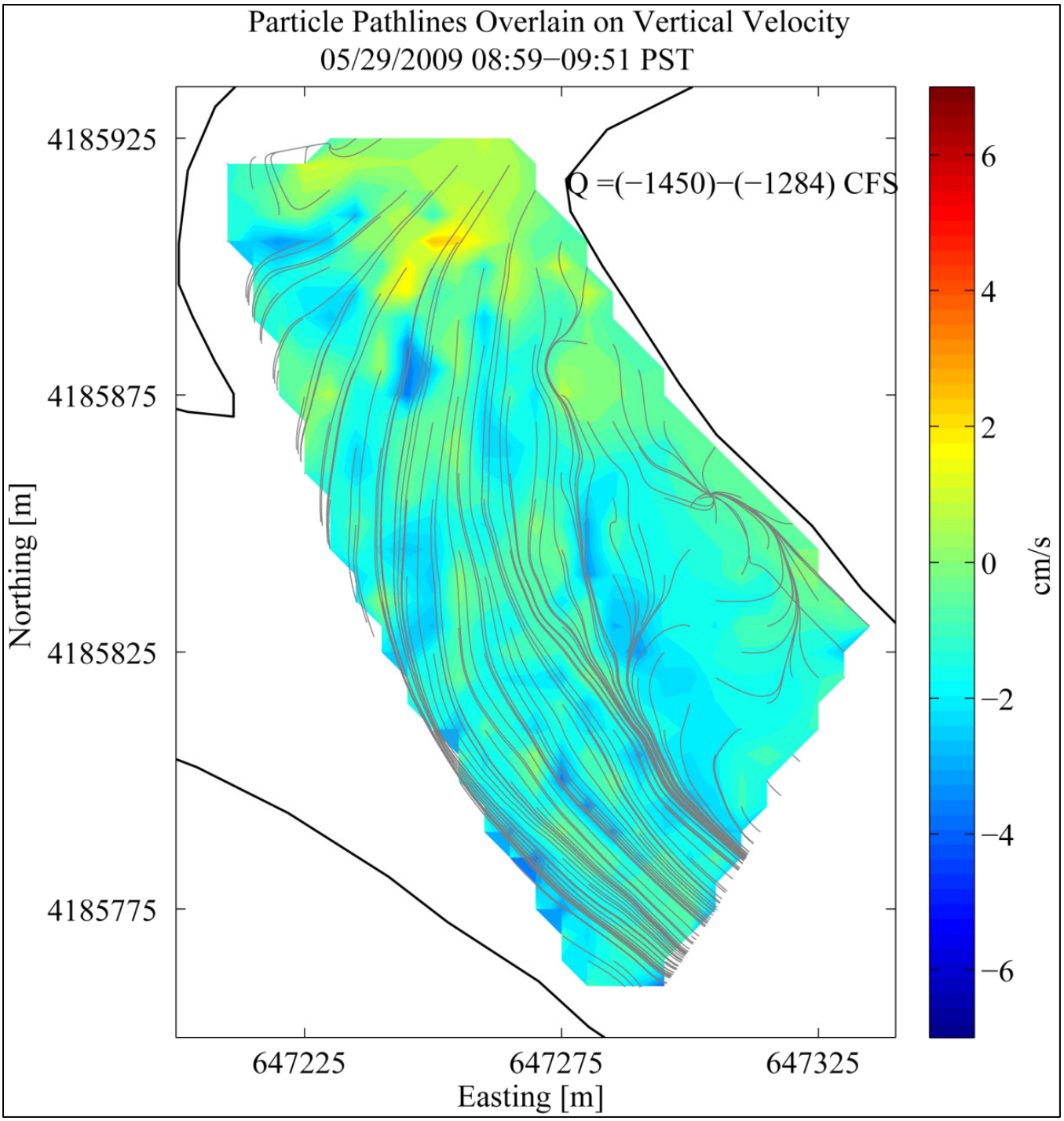
Source: Present study

Figure 3-8 **Vertical Velocity (cm/s) and Particle Pathlines Estimated from Data Collected with a DL-ADCP at the Head of Old River, 6/5/2009, 0939–1020 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 1,438 to 1,470 cfs**



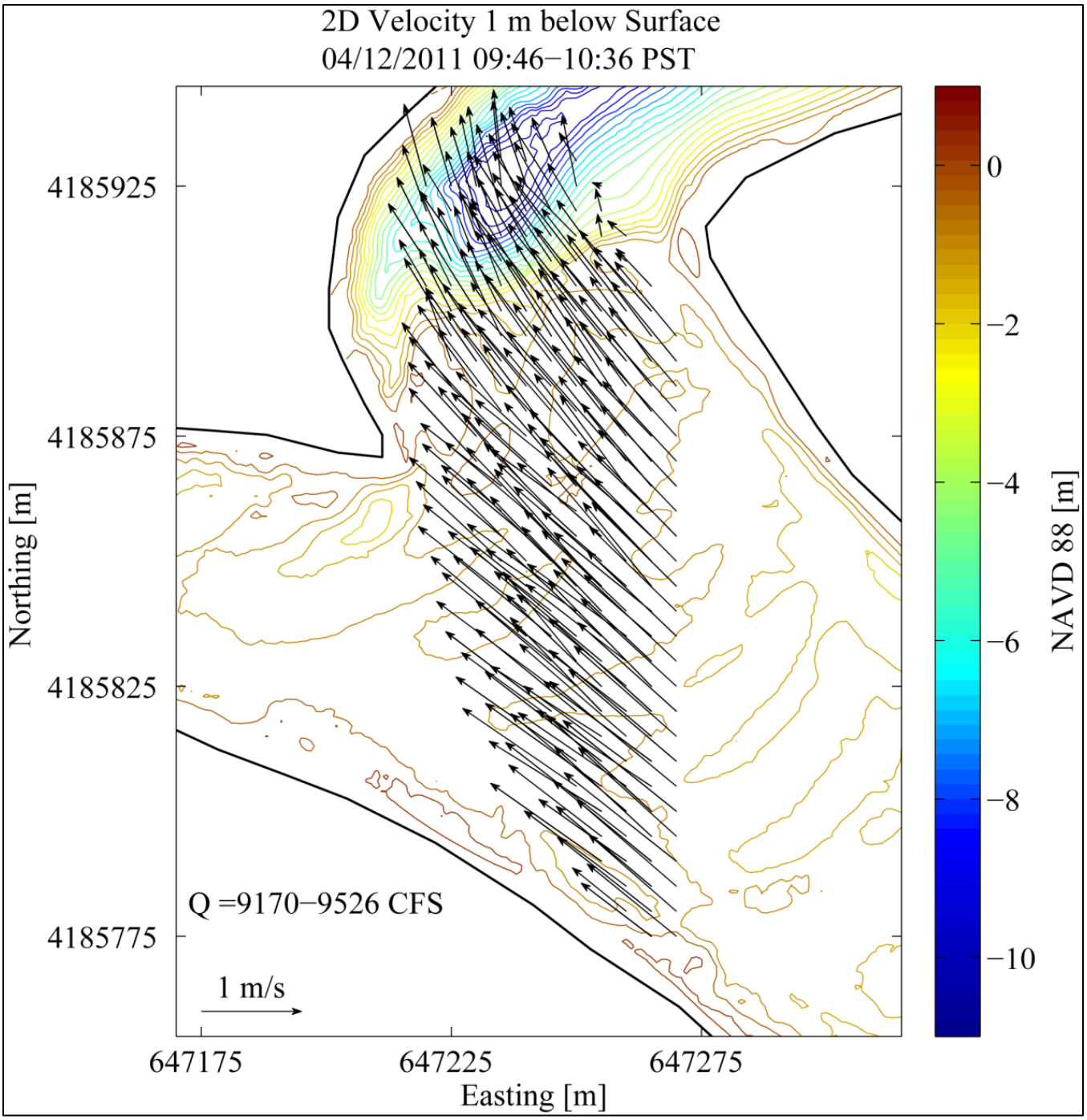
Source: Present study

Figure 3-9 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a DL-ADCP at the Head of Old River, 5/29/2009, 0859–0951 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of -1,450 to -1,284 cfs**



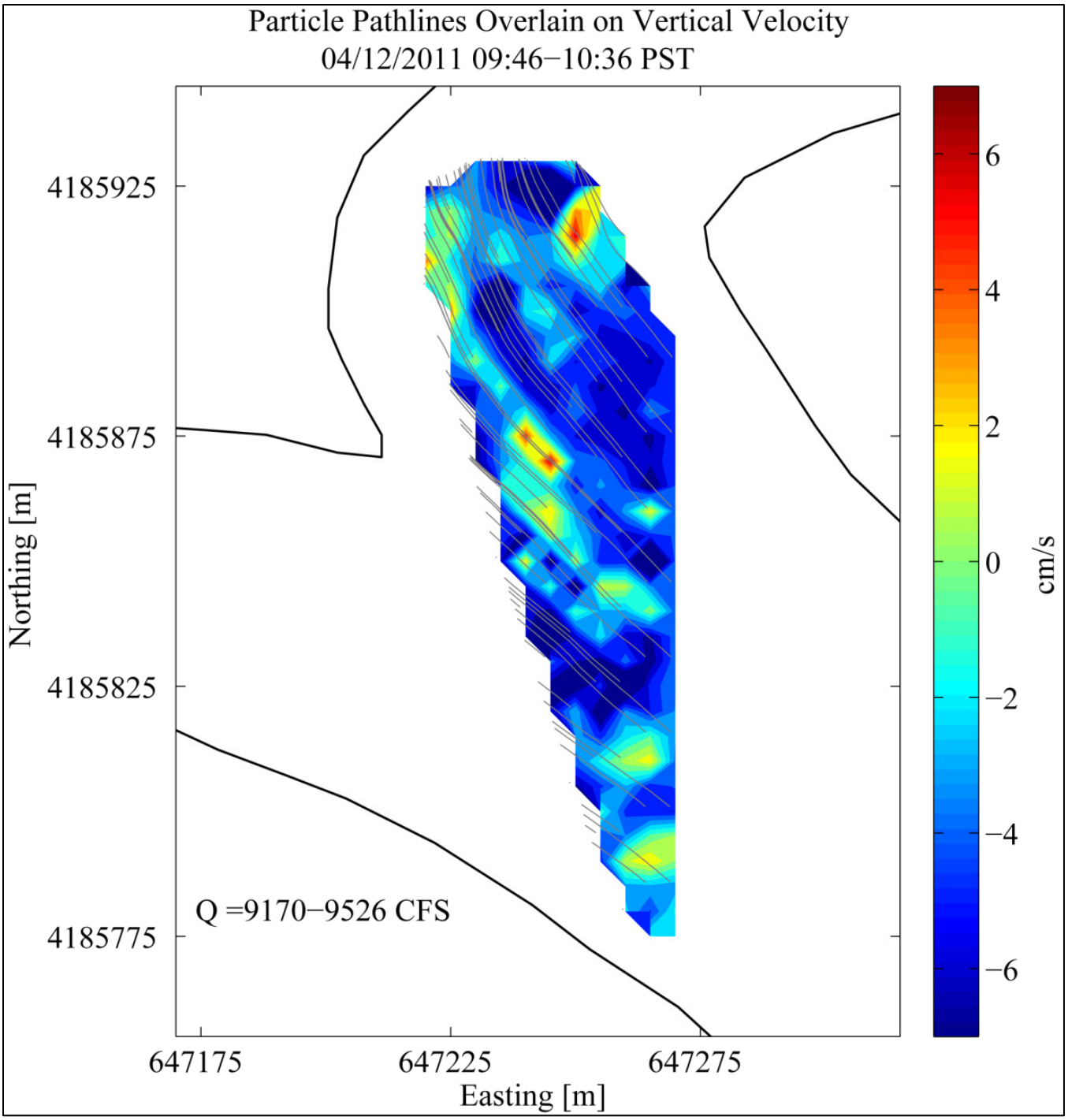
Source: Present study

Figure 3-10 **Vertical Velocity (cm/s) and Particle Pathlines Estimated from Data Collected with a DL-ADCP at the Head of Old River, 5/29/2009, 0859–0951 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of -1,450 to -1,284 cfs**



Source: Present study

Figure 3-11 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a DL-ADCP at the Head of Old River, 4/12/2011, 0946–1036 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 9,170 to 9,526 cfs**



Source: Present study

Figure 3-12 **Vertical Velocity (cm/s) and Particle Pathlines Estimated from Data Collected with a DL-ADCP at the Head of Old River, 4/12/2011, 0946–1036 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 9,170 to 9,526 cfs**

VELOCITY MODELING OF 2012 (PHYSICAL ROCK BARRIER)

The set of observations from the 2012 SL2D velocity fields are the most extensive available over a range of discharge values. The most notable observations are described herein. At low discharge (approximately 780 cfs; the 5th percentile discharge in 2012), the flow field does not exhibit much variability, and the velocity vectors near the barrier are low (Figures 3-13 and 3-14).

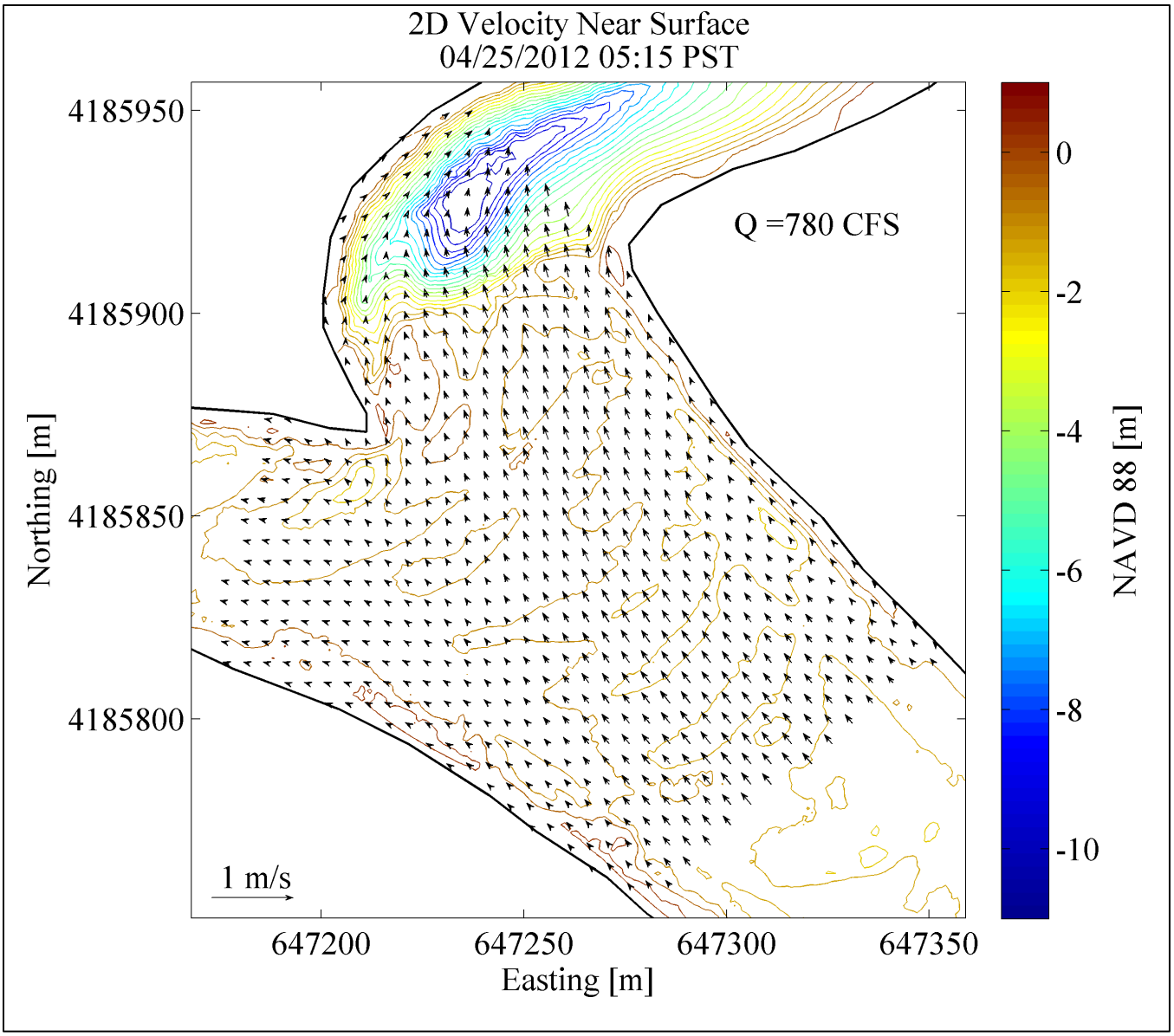
At moderate discharge values (1,500 to 1,970 cfs; the 25th to 50th percentile discharge in 2012), more variability occurred in the flow field, with higher velocities mid-channel and near the scour hole downstream of the divergence, and low velocities near the barrier (Figures 3-15, 3-16, 3-17, and 3-18). Two large-scale eddies appear at these discharge levels: one eddy forms near the barrier with a counter-clockwise (CCW) rotation, and a smaller eddy forms near the left bank adjacent to the scour hole, also with a CCW rotation.

At higher discharge values (2,250 to 2,660 cfs; the 75th to 95th percentile discharge in 2012), the flow field remains consistent, with higher velocity magnitudes (Figures 3-19, 3-20, 3-21, and 3-22). The eddy near the barrier becomes larger during moderate discharges. The eddy near the scour hole is not consistently present throughout the set of observations. As noted in the following section ("Comparison of DL2D and SL2D"), the SL2D velocity fields do not represent the eddy near the scour hole consistently in comparison to the DL2D.

COMPARISON OF DL2D AND SL2D

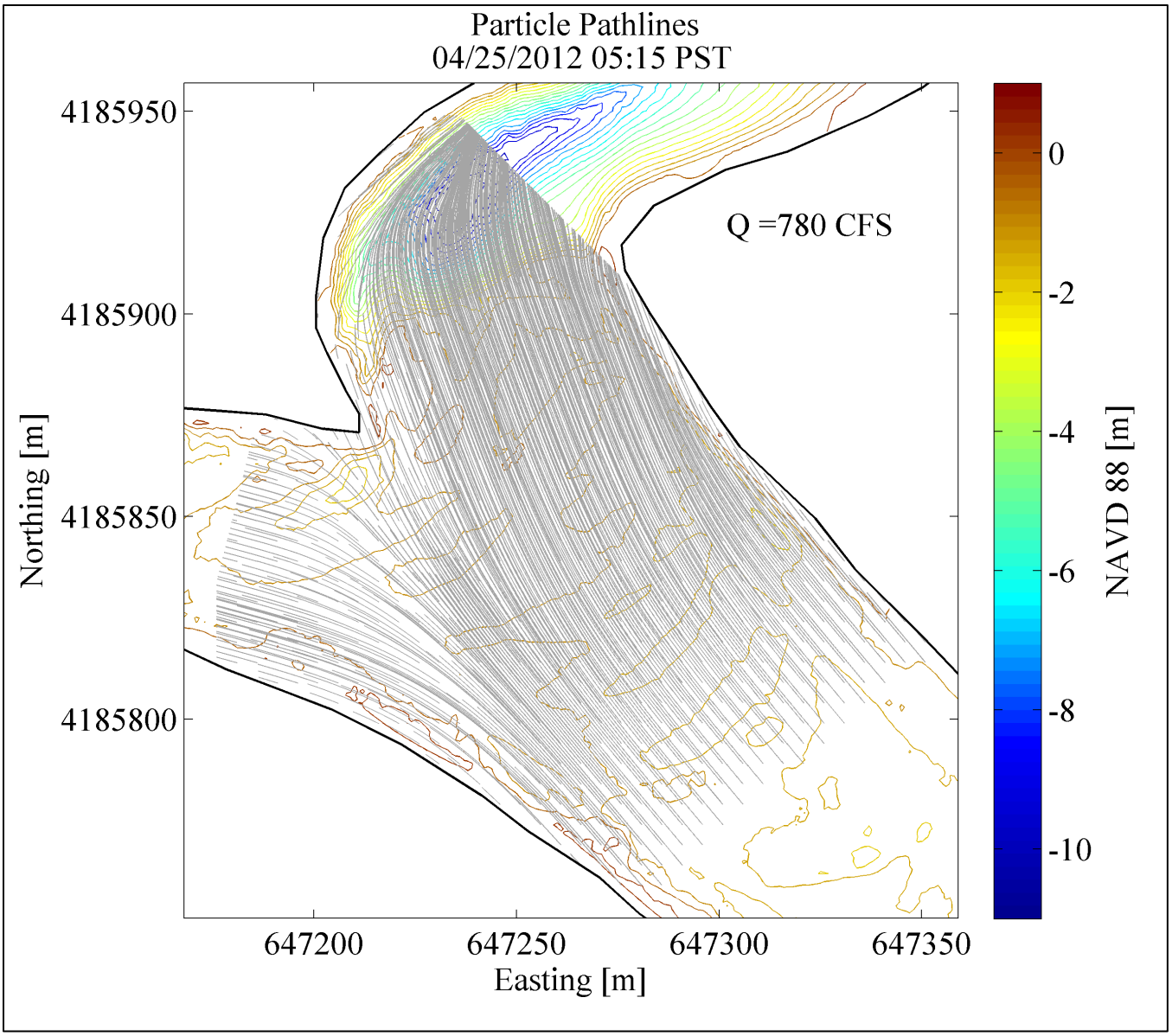
A comparison was made of the DL2D and SL2D velocity fields. The DL-ADCP data collected on May 8 and 30, 2012 were from a range of discharge values (1,840 to 2,660 cfs). These data were collected near the physical rock barrier and near the scour hole. The DL2D velocity field is considered more accurate because the interpolation was based on larger data density, but fewer observations exist over a smaller range of discharge. The most important observations from these comparisons are as follows:

- The SL2D velocity field accurately represented the velocity variability throughout the domain, except near the barrier, where the magnitude of the velocity vectors from the SL2D velocity field are smaller than those from the DL2D velocity field.
- The SL2D velocity field failed to capture or fully represent the eddy that was present near the scour hole for all observations, but this eddy was seen in nearly all of the observations of the DL2D velocity field.
- The eddy near the barrier appears to be accurately captured by the SL2D velocity field and was present in the DL2D velocity field.



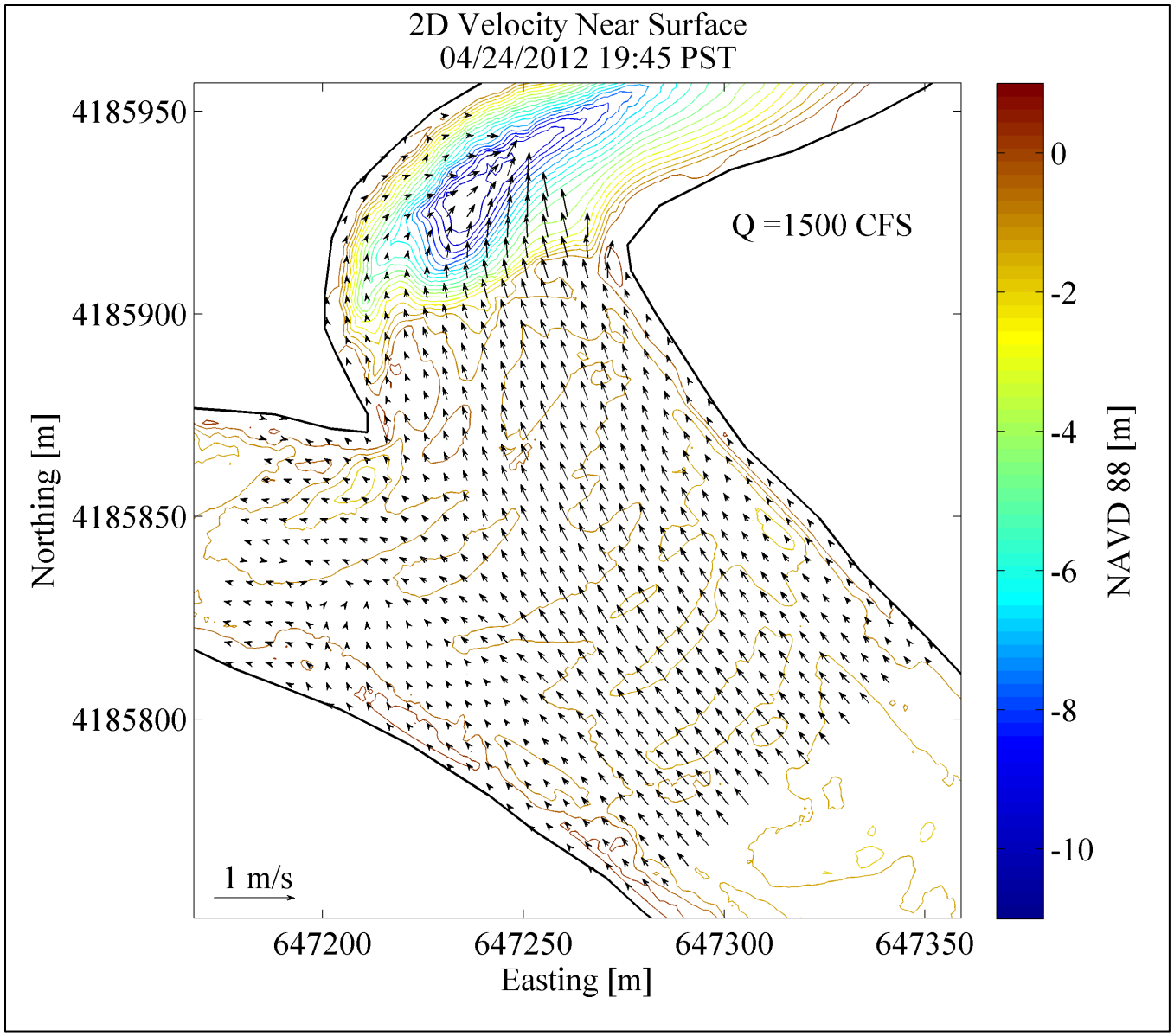
Source: Present study

Figure 3-13 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 4/25/2012, 0515 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 780 cfs**



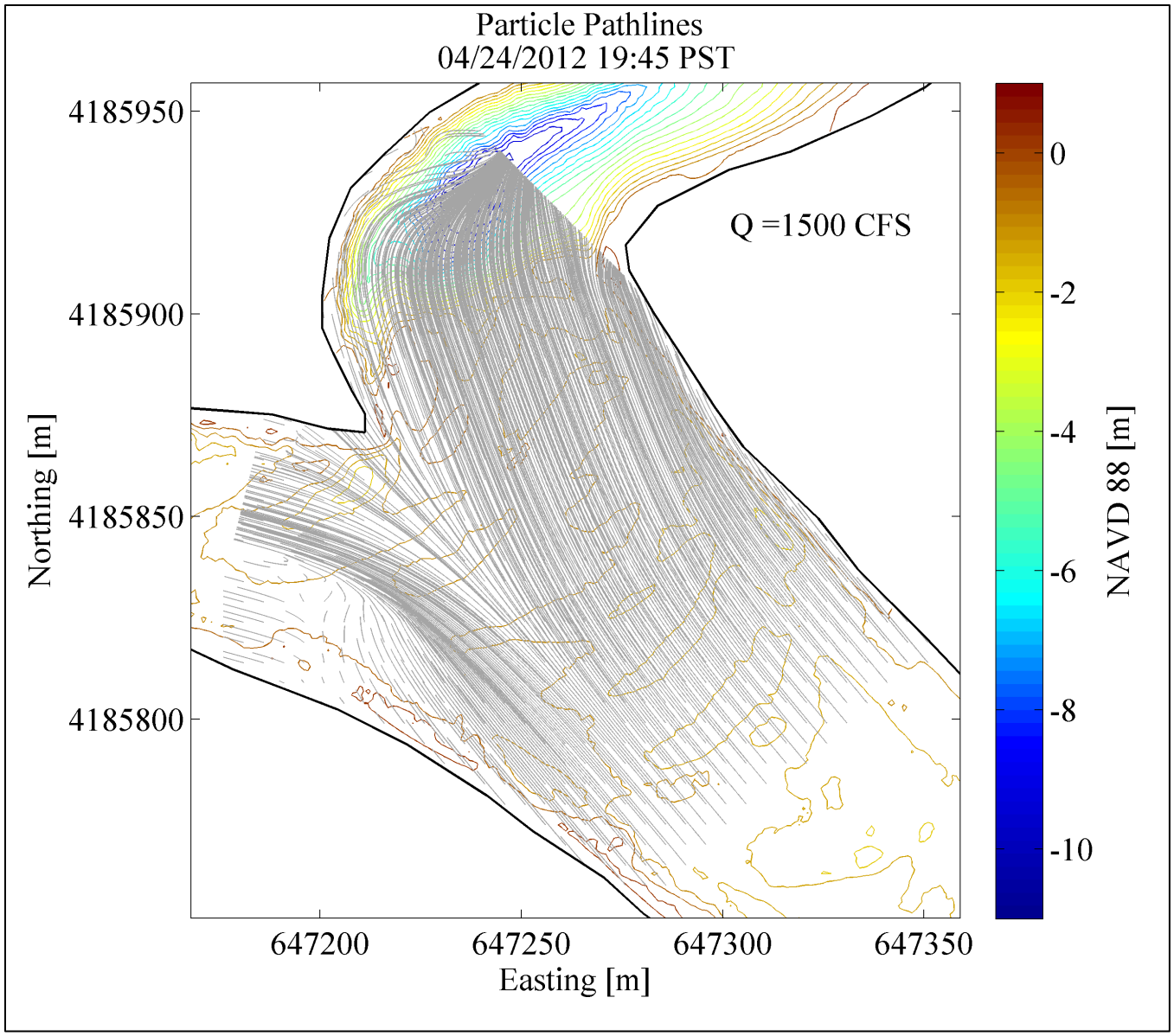
Source: Present study

Figure 3-14 Two-Dimensional Near-Surface Particle Pathlines (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 4/25/2012, 0515 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 780 cfs



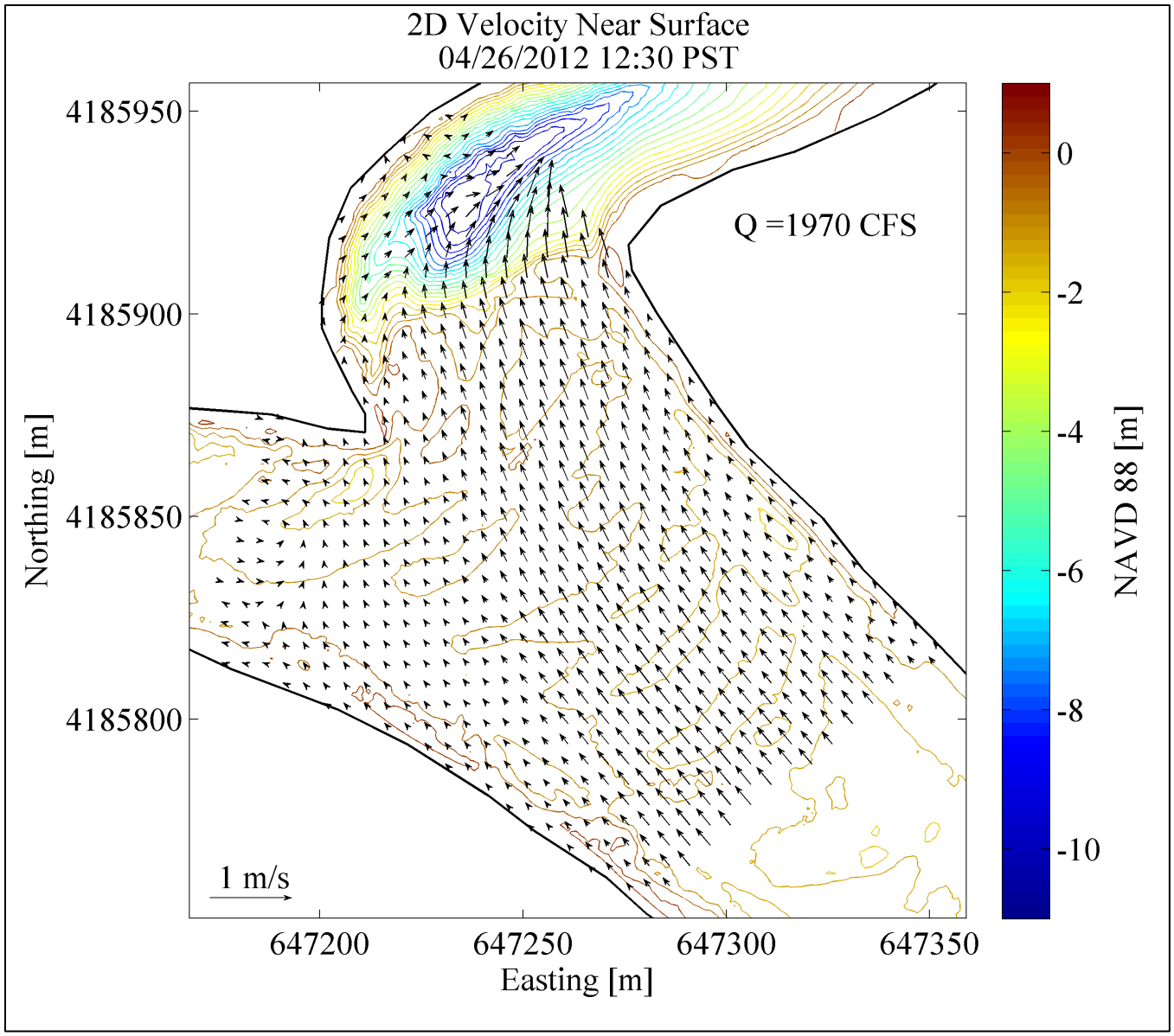
Source: Present study

Figure 3-15 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 4/24/2012, 1945 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 1,500 cfs**



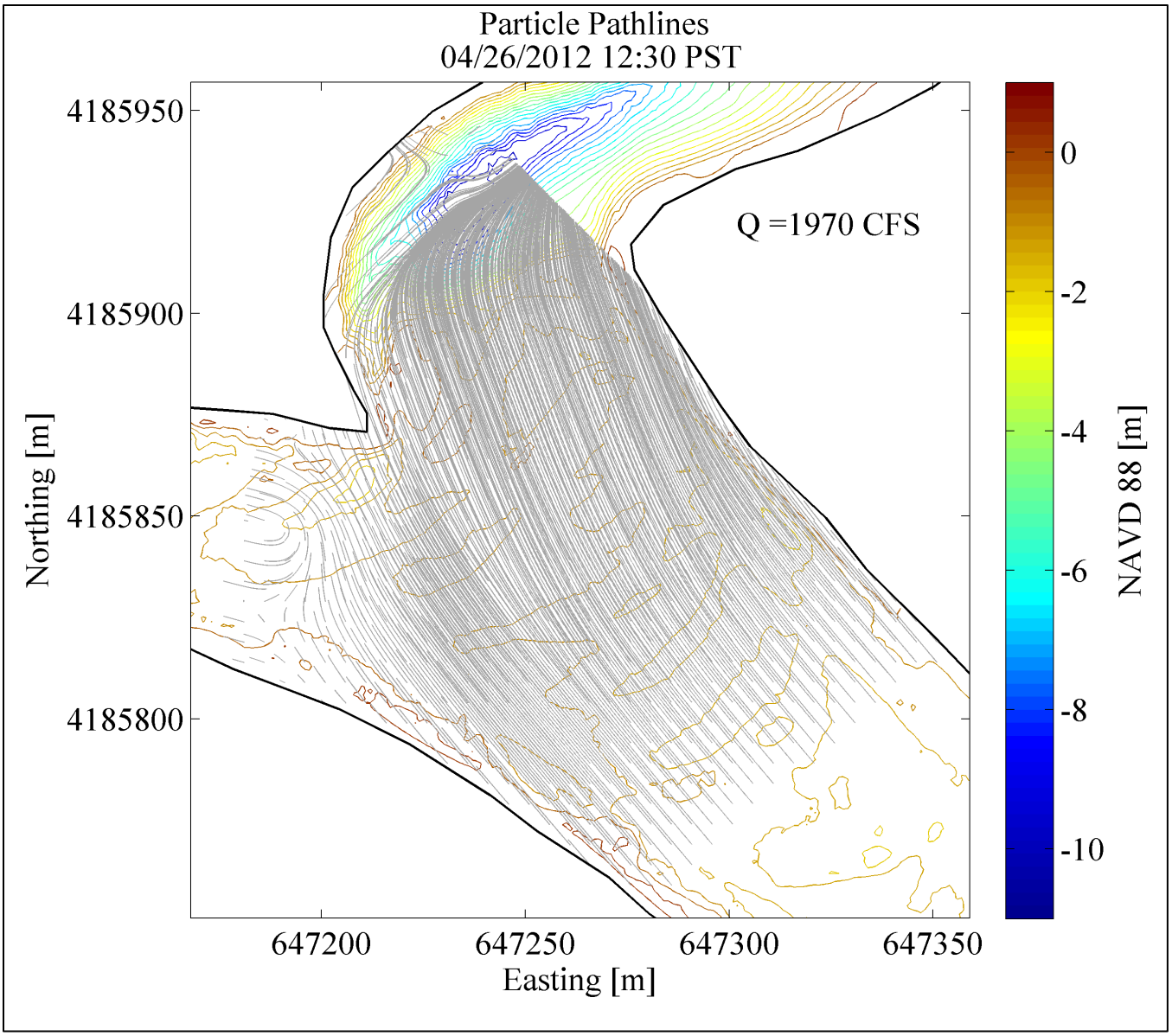
Source: Present study

Figure 3-16 Two-Dimensional Near-Surface Particle Pathlines (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 4/24/2012, 1945 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 1,500 cfs



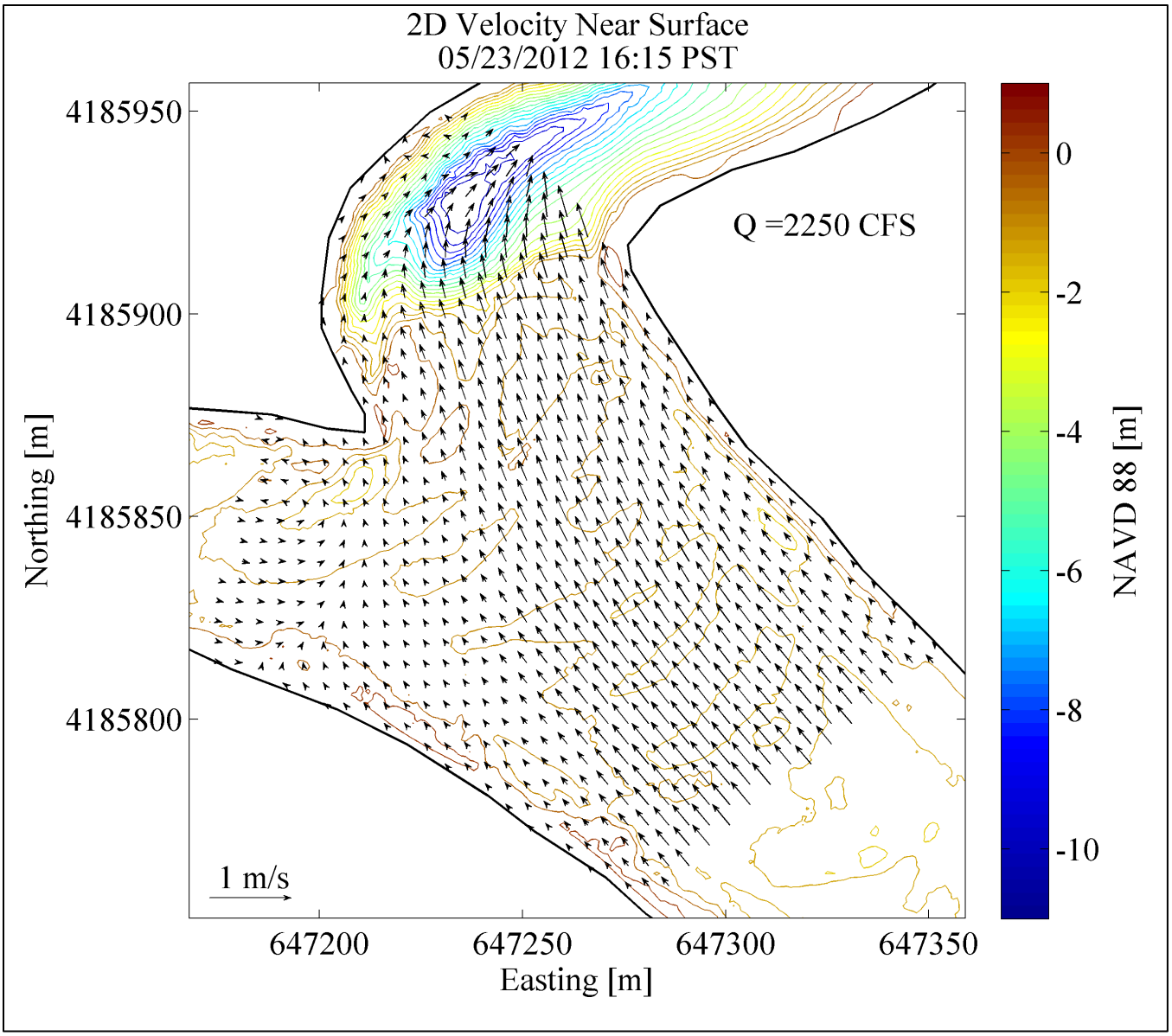
Source: Present study

Figure 3-17 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 4/26/2012, 1230 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 1,970 cfs**



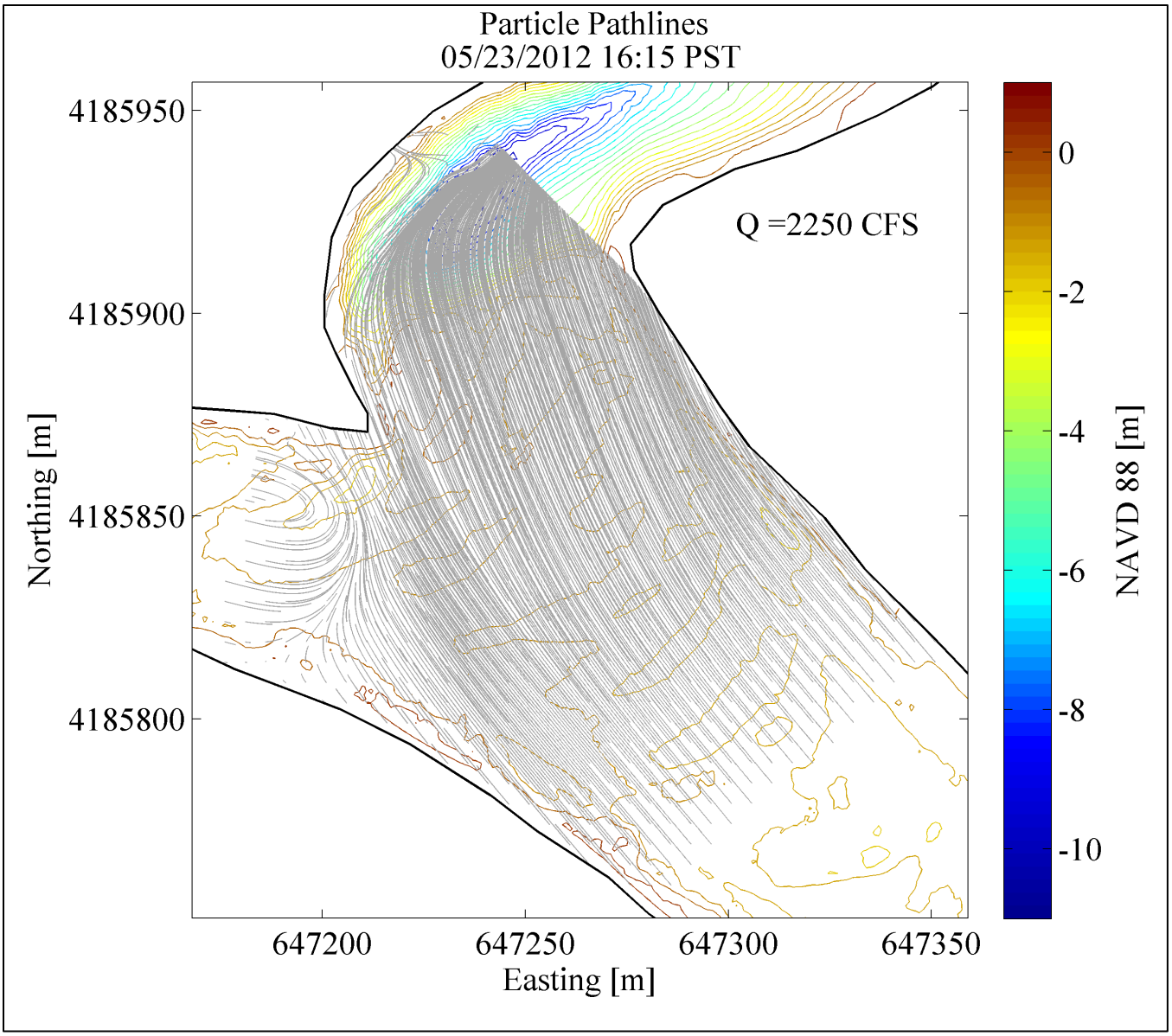
Source: Present study

Figure 3-18 Two-Dimensional Near-Surface Particle Pathlines (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 4/26/2012, 1230 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 1,970 cfs



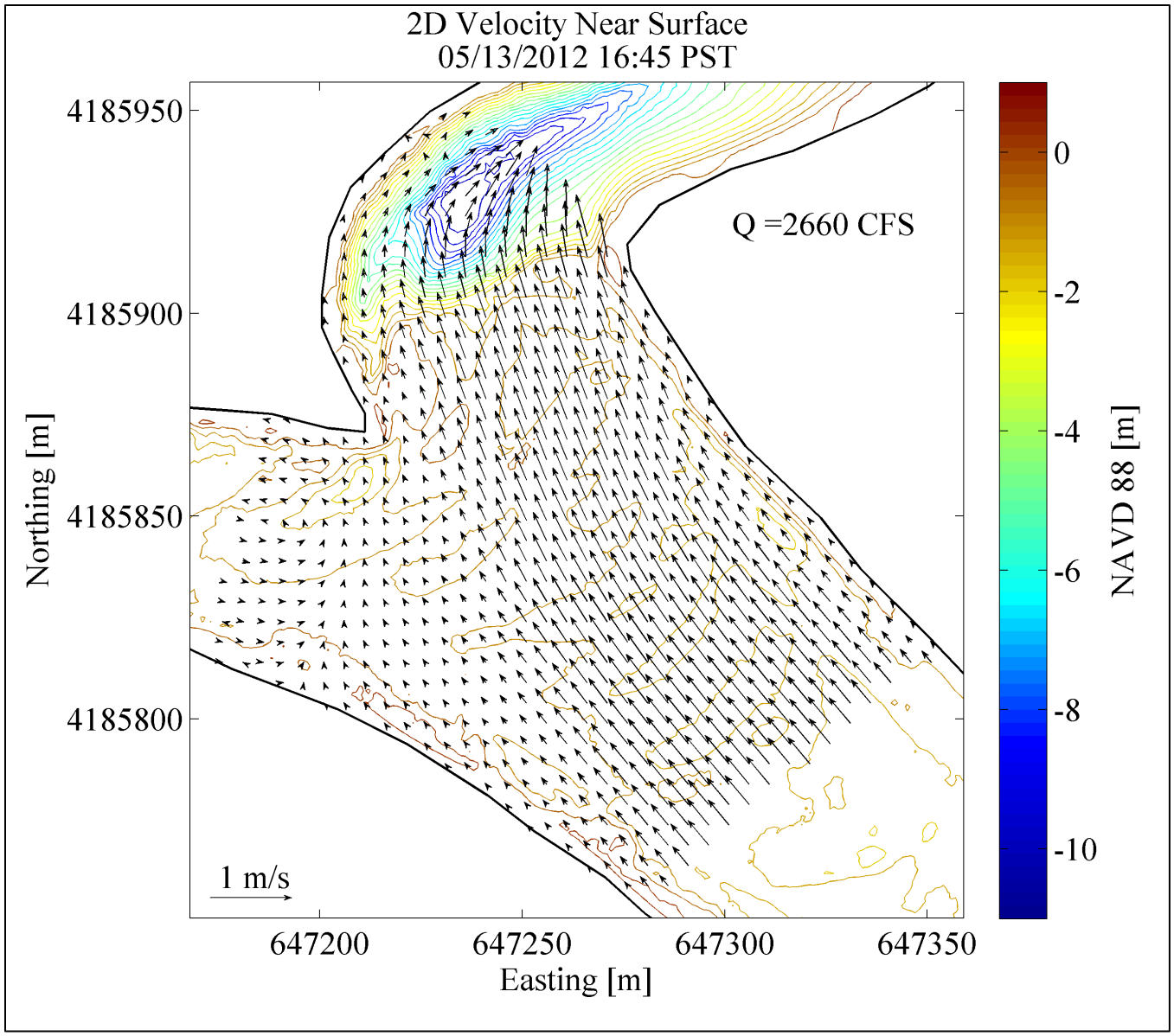
Source: Present study

Figure 3-19 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 5/23/2012, 1615 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 2,250 cfs**



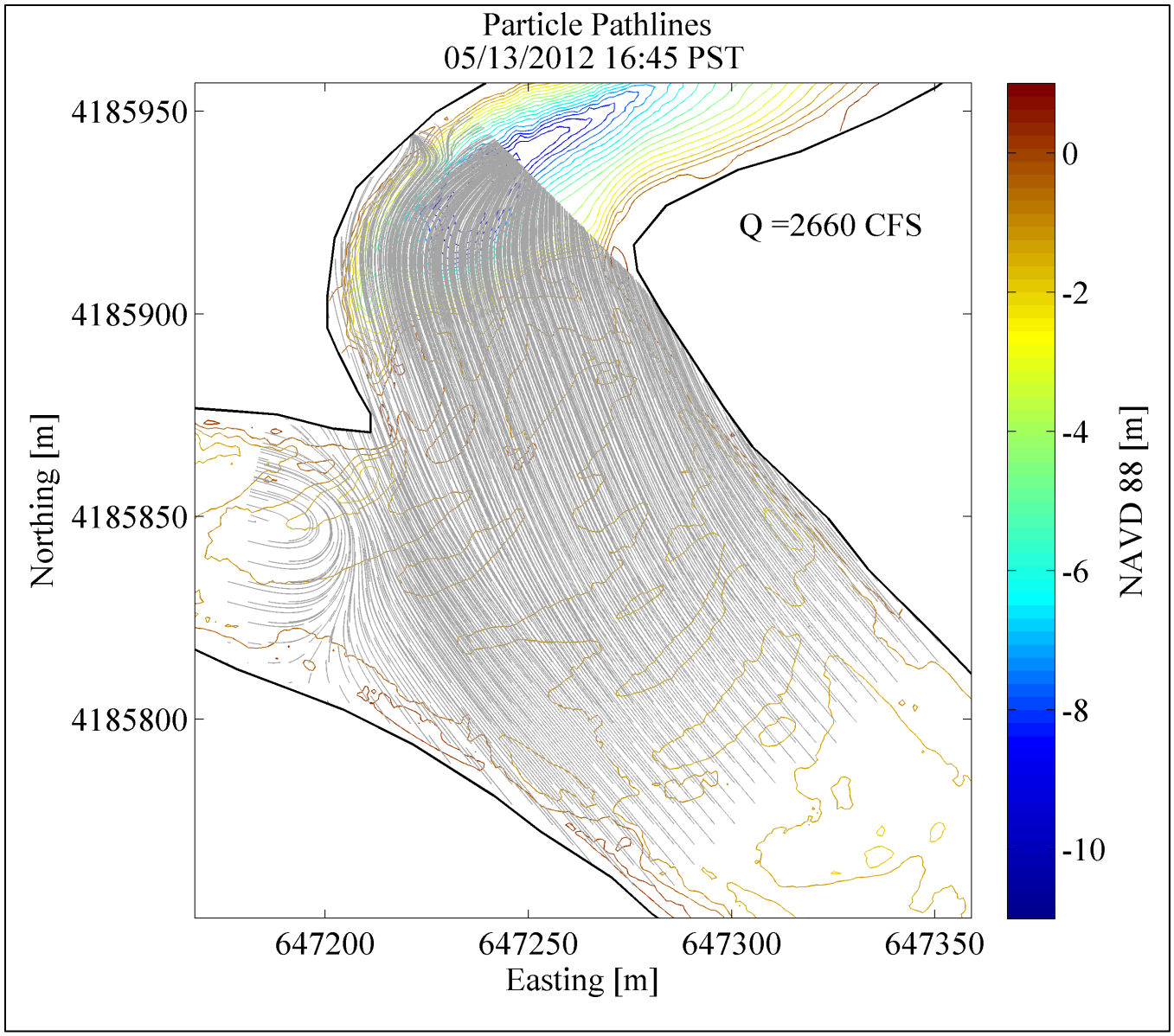
Source: Present study

Figure 3-20 Two-Dimensional Near-Surface Particle Pathlines (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 5/23/2012, 1615 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 2,250 cfs



Source: Present study

Figure 3-21 **Two-Dimensional Near-Surface Velocity Vectors (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 5/13/2012, 1645 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of 2,660 cfs**



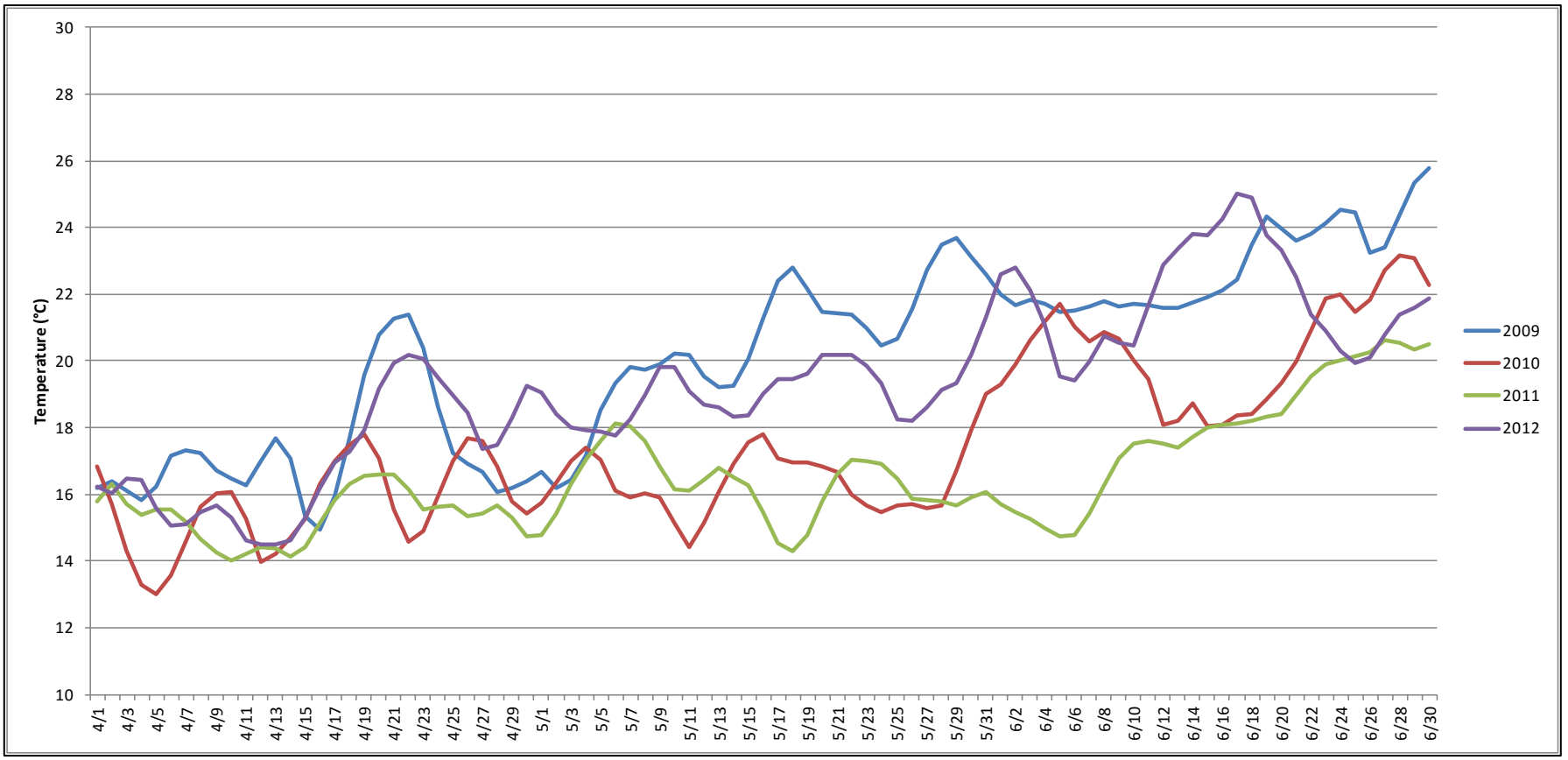
Source: Present study

Figure 3-22 Two-Dimensional Near-Surface Particle Pathlines (m/s) Estimated from Data Collected with a SL-ADCP at the Head of Old River, 5/13/2012, 1645 PST, with River Discharge in the San Joaquin River near Lathrop (Q) of cfs

3.3 WATER TEMPERATURE

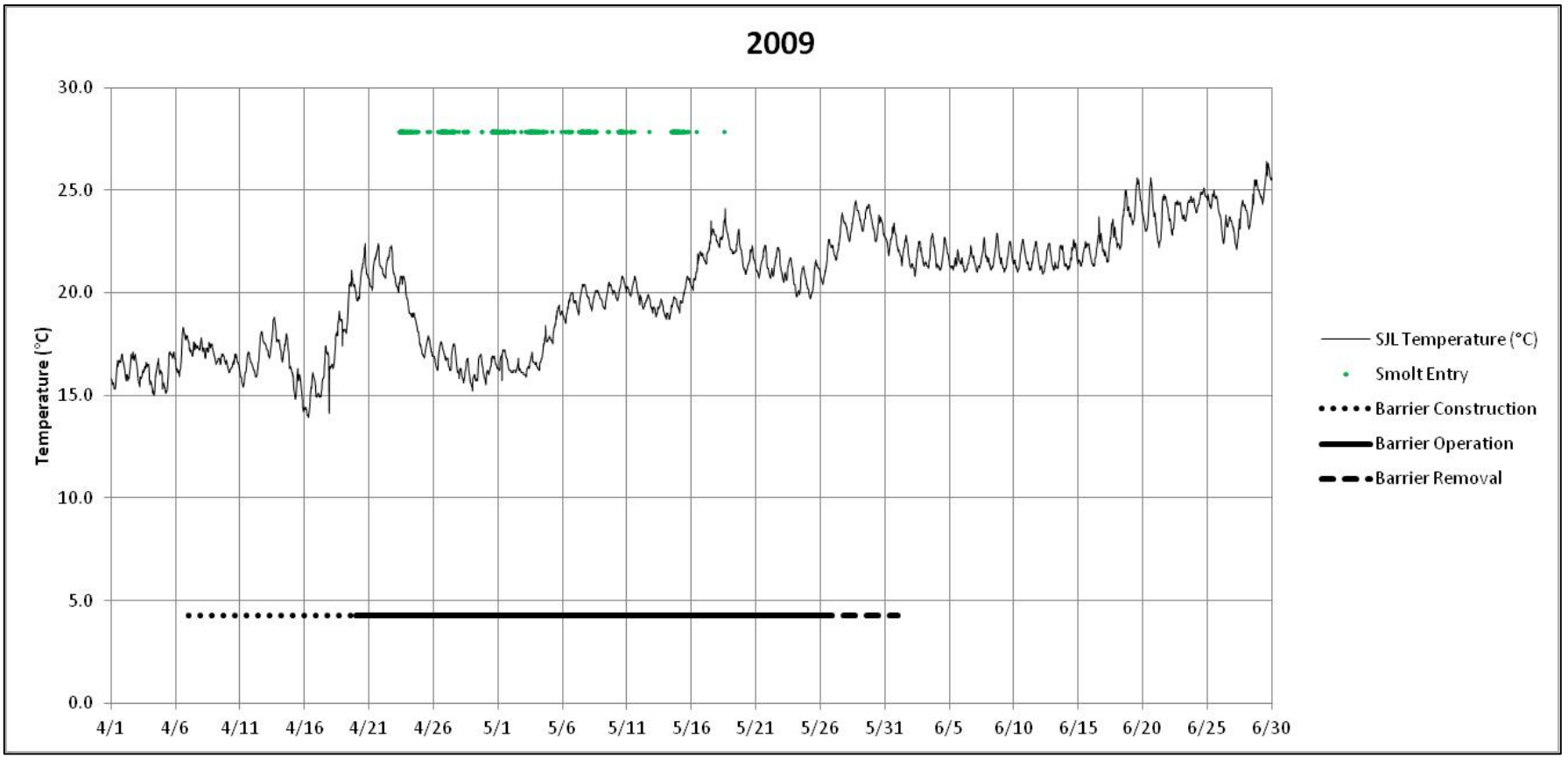
3.3.1 2009 TEMPERATURE

Mean daily water temperature between April 1 and June 30 was higher in 2009 compared to 2010 and 2011, but more similar to 2012 (Figure 3-23). Between April 1 and June 30, 2009, the water temperature in the San Joaquin River at the closest gauge in physical proximity (SJL) to the HOR study area ranged from 13.9 to 26.9 °C (Figure 3-24). When tagged juvenile Chinook salmon were in the water, the mean temperature in 2009 generally was warmer than in 2010 and 2011, but was similar to the mean temperature in 2012 (Table 3-3; Figures 3-24, 3-25, 3-26, and 3-27).



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Figure 3-23 **Daily Mean Water Temperature (°C) in the San Joaquin River at Lathrop (SJL), 4/1–6/30, 2009–2012**

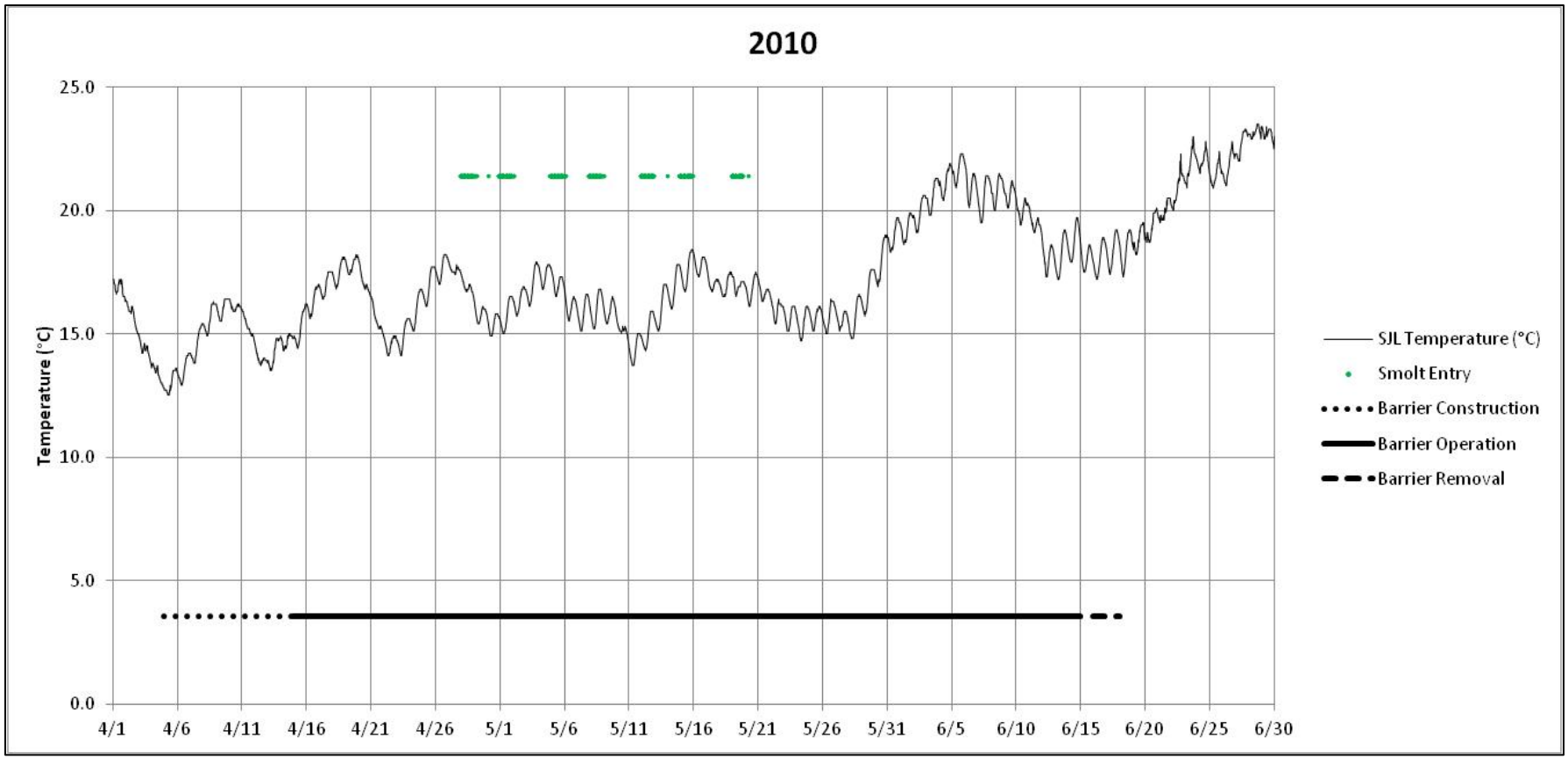


Sources: Baldwin, pers. comm.; 2013; Dempsey, pers. comm., 2013

Note: The barrier referred to in the legend was a non-physical fish barrier called a BAFF (Fish Guidance Systems Ltd, Southampton, UK). Barrier operation was not continuous, with the BAFF off approximately 50% of the time during the period of BAFF operation.

Figure 3-24

Water Temperature (°C), Juvenile Chinook Salmon Releases and Barrier Status in the San Joaquin River at Lathrop Gauge from 4/1/09 through 6/30/09

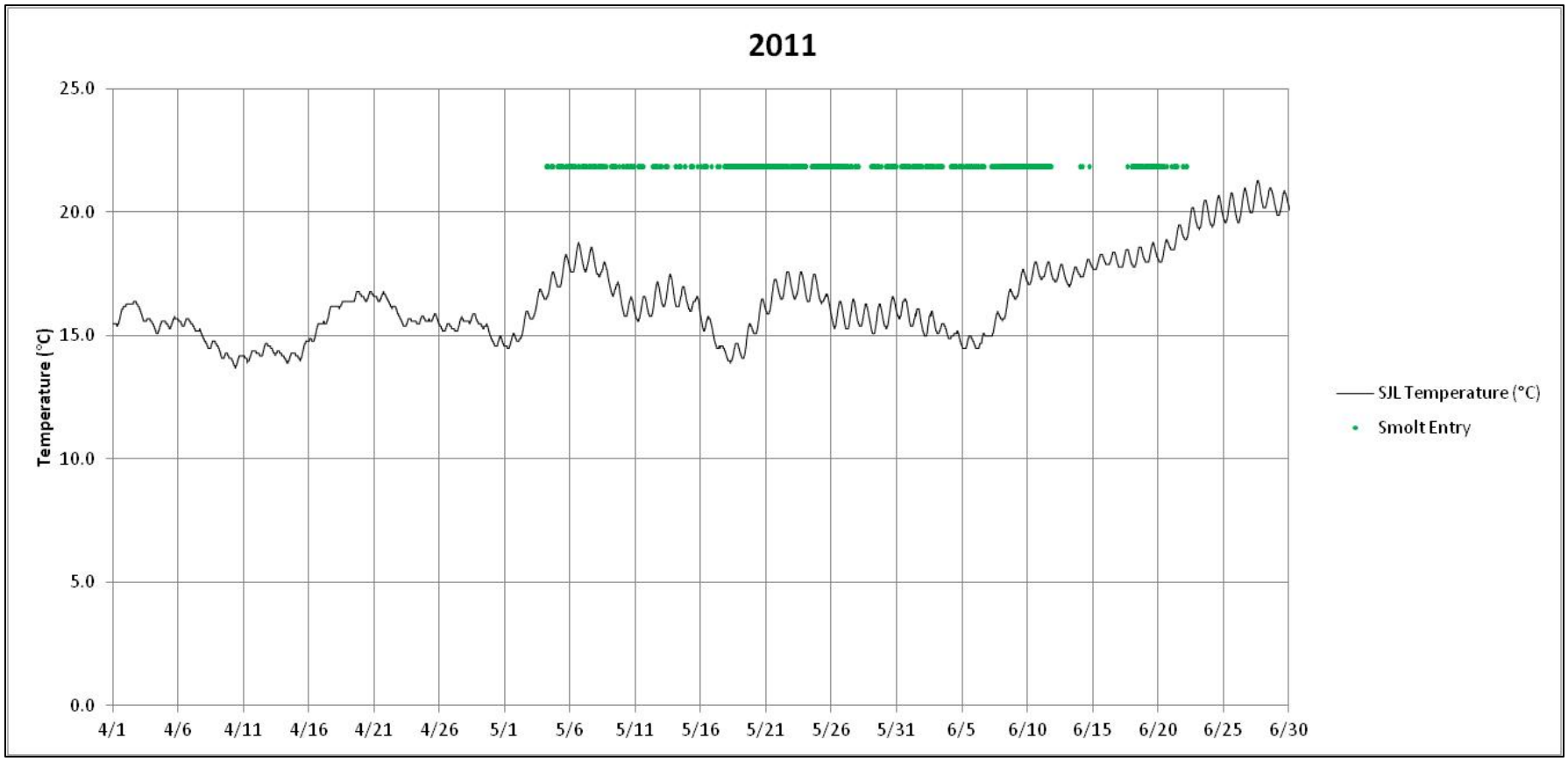


Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: The barrier referred to in the legend was a non-physical fish barrier called a BAFF (Fish Guidance Systems Ltd, Southampton, UK). Barrier operation was not continuous, with the BAFF off approximately 50% of the time during the period of BAFF operation.

Figure 3-25

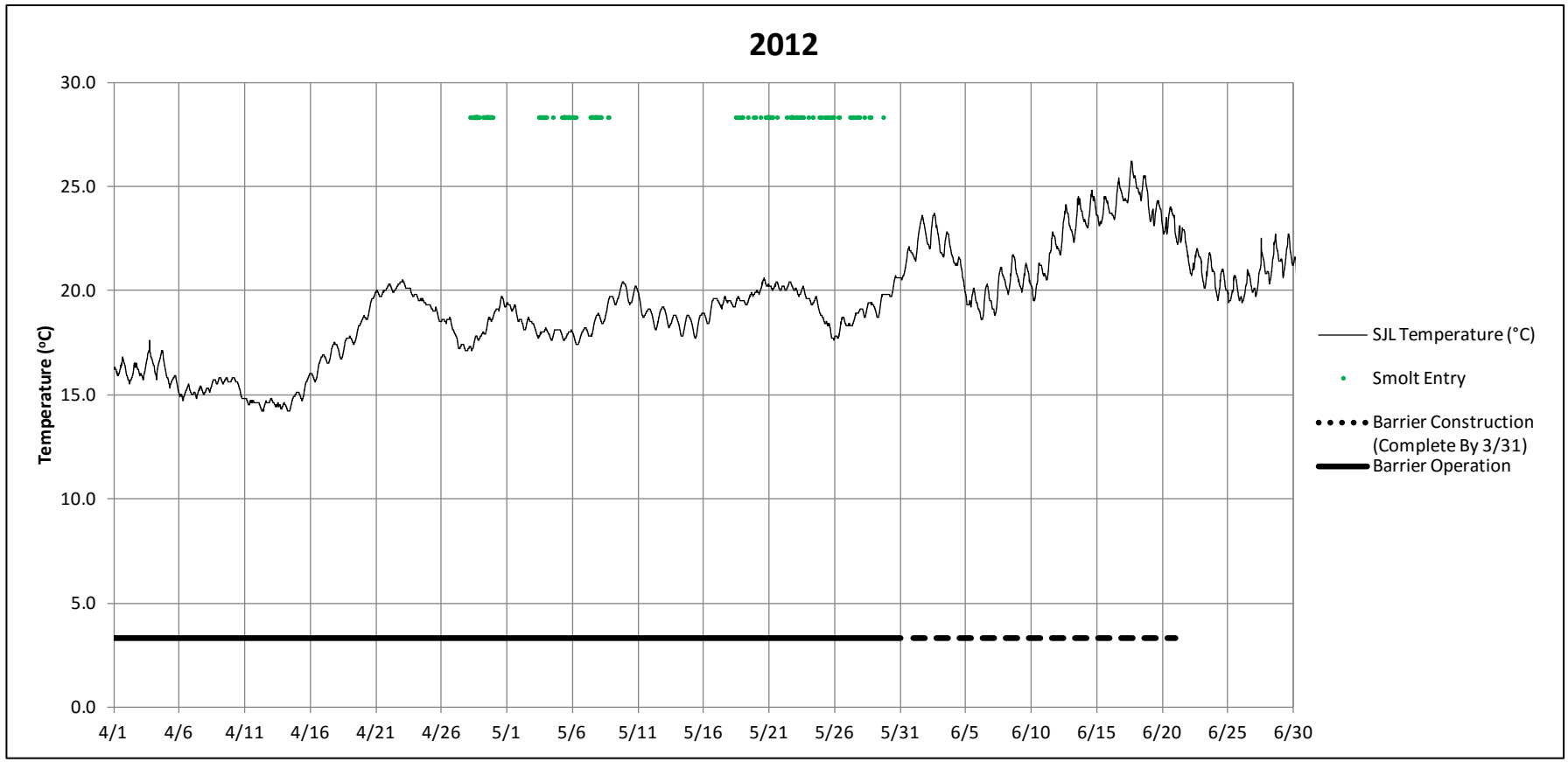
Water Temperature (°C), Juvenile Chinook Salmon Releases and Barrier Status in the San Joaquin River at Lathrop Gauge from 4/1/10 through 6/30/10



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: No barrier was installed or operated during this period.

Figure 3-26 **Water Temperature (°C) and Juvenile Chinook Salmon Releases in the San Joaquin River at Lathrop Gauge from 4/1/11 through 6/30/11**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: The barrier installed during this period was a rock barrier with eight culverts.

Figure 3-27 **Water Temperature (°C), Juvenile Chinook Salmon Releases and Barrier Status in the San Joaquin River at Lathrop Gauge from 4/1/12 through 6/30/12**

Table 3-3
Descriptive Statistics for 2009–2012 Water Temperature in the San Joaquin River at the SJL Gauge when Tagged Juvenile Salmonids were at the HOR Study Area

			SJL Temperature (°C)				
Year	First Fish[1]	Last Fish[2]	Mean	Standard Deviation	Minimum	Maximum	Count
2009	4/23/09 8:24	5/18/09 13:48	18.6	1.9	15.2	23.6	2422
2010	4/27/10 22:25	5/20/10 5:54	16.4	1.0	13.7	18.4	2143
2011	5/4/11 2:51	6/22/11 4:24	16.6	1.2	13.9	19.5	4712
2012	4/28/12 4:13	5/29/12 16:35	18.9	0.8	17.1	20.6	3026

Notes: HOR = Head of River; SJL = San Joaquin River at Lathrop

The SJL gauge is the closest gauge in physical proximity to the HOR study area, and was 0.5 km of the HOR site. The periods reported here are those when experimentally released fish were nearest the 2009 BAFF line (in 2009, 2011, and 2012) and nearest the 2010 BAFF line (in 2010).

[1] Date/time when the first tagged salmonids was nearest the BAFF line.

[2] Date/time the last tagged salmonids was nearest the BAFF line.

Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Although 2009 and 2012 were similar in mean water temperature, differences existed. During the tagged juvenile Chinook salmon release period, the water temperature in 2009 increased to 22 °C, a critical temperature that can cause major mortality in wild populations of Chinook salmon (Moyle 2002), for 30 hours during one interval; this never occurred in 2012 (see temperature maxima in Table 3-3). Furthermore, the standard deviation (SD) of water temperature was considerably higher in 2009 than in 2012 (Table 3-3).

Although juvenile steelhead were not released, by June 12, temperatures at the SJL gauge had risen to a point where the respiratory efficiency of steelhead would be affected (21 °C) (Hooper 1973). This date was earlier than in any other year studied (Table 3-4). Wild, non-hatchery steelhead could have been passing through the HOR study area (Table B-2 in Appendix B, "Focal Fish Species Information"). Experimental releases constrain the study juvenile fish to migrate at prescribed periods, whereas wild, non-hatchery fish may respond more strongly to environmental cues, such as water temperature.

Table 3-4
Day of the Year at which the Water Temperature in the San Joaquin River at SJL Gauge Reached and Remained at Least 15 Days at Two Critical Temperatures for Juvenile Salmonids

Year	Temperature > 21.0 °C[1]	Temperature > 23.9 °C[2]
2009	June 12	July 14
2010	July 5	July 10
2011	July 27	Not Exceeded
2012	June 29	July 7

Notes: SJL = San Joaquin River at Lathrop

For Chinook salmon, major mortality occurred at 22–23 °C in wild populations, and very few individuals survived temperatures greater than 24 °C (Moyle 2002).

[1] Temperature at which steelhead juveniles had difficulty absorbing oxygen from the water, 21.0 °C (Hooper 1973)

[2] Steelhead upper lethal thermal limit, 23.9 °C (Bell 1986)

Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

3.3.2 2010 TEMPERATURE

From April 1, 2010, through June 30, 2010, the water temperature at the SJL gauge ranged from 12.5 to 23.5 °C (Figure 3-25). When tagged juvenile Chinook salmon were present in the study area, the mean water temperature in 2010 was lower than in any other year, but was very similar to 2011 (Table 3-3; Figures 3-23, 3.24, 3-25, and 3-26). Furthermore, in 2010, it took longer to reach 21 °C and remain there for 15 days or more, longer than any year except 2011 (Table 3-4).

3.3.3 2011 TEMPERATURE

From April 1 through June 30, 2011, the water temperature at the SJL gauge ranged from 13.7 to 21.3 °C (Figure 3-26). The water temperature in 2011 was consistently cooler than in 2009 and throughout spring and summer of 2012 (Figure 3-23). Although 2011 did not have the lowest mean water temperature (Table 3-3), the temperature never increased to 23.9 °C, the upper lethal limit for steelhead (Bell 1986). Among the 4 years included in this study, the only year that the water temperature never exceeded 23.9 °C was 2011 (Table 3-4).

3.3.4 2012 TEMPERATURE

From April 1 through June 30, 2012, the water temperature in the San Joaquin River at Lathrop ranged from 14.2 to 26.2 °C (Figure 3-27). When tagged juvenile Chinook salmon and steelhead were present in the study area, the mean water temperature in 2012 was higher than in any other year. Furthermore, the mean 2012 water temperatures generally were warmer than 2010 and 2011, but similar to 2009 temperatures (Table 3-3; Figures 3-23 to 3-27). Also, by June 29, 2012, water temperatures at the SJL gauge had risen to a point where steelhead respiratory efficiency was affected (21 °C) (Hooper 1973).

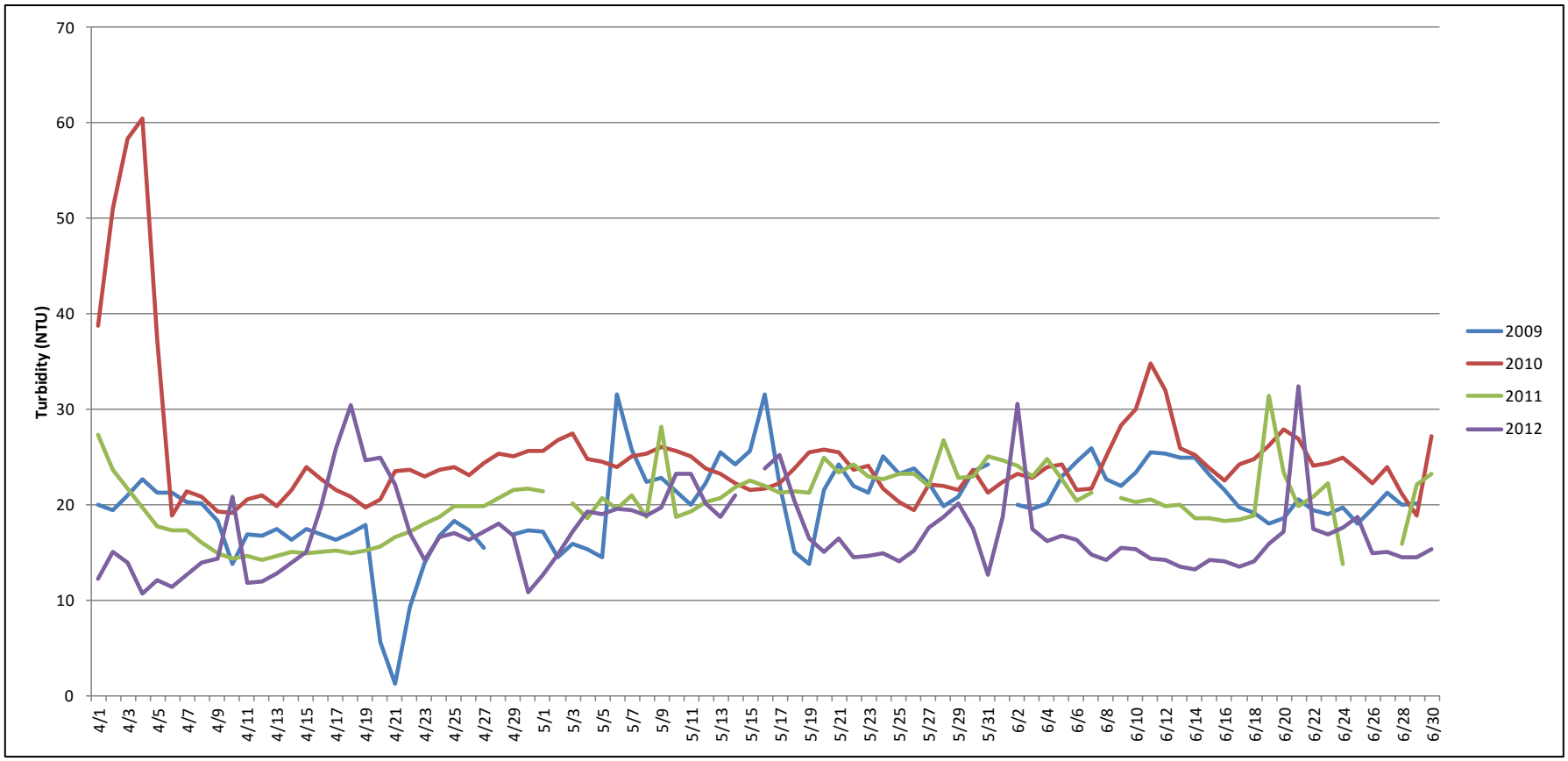
3.4 WATER CLARITY (TURBIDITY)

3.4.1 2009 TURBIDITY

Turbidity varied between years (Figure 3-28). From April 1 through June 30, 2009, the turbidity at MSD, the closest gauge in physical proximity to the HOR study area (4.6 km), ranged from 9.1 to 48.3 Nephelometric Turbidity Units (NTU) (Figure 3-29). When tagged juvenile Chinook salmon were recorded by the receivers, the mean turbidity in 2009 generally was lower than in 2010, but was similar to 2011 and 2012 turbidity (Table 3-5; Figures 3-28, 3-29, 3-30, 3-31, and 3-32). The turbidity also was more variable in 2009 than in any other year (Table 3-5).

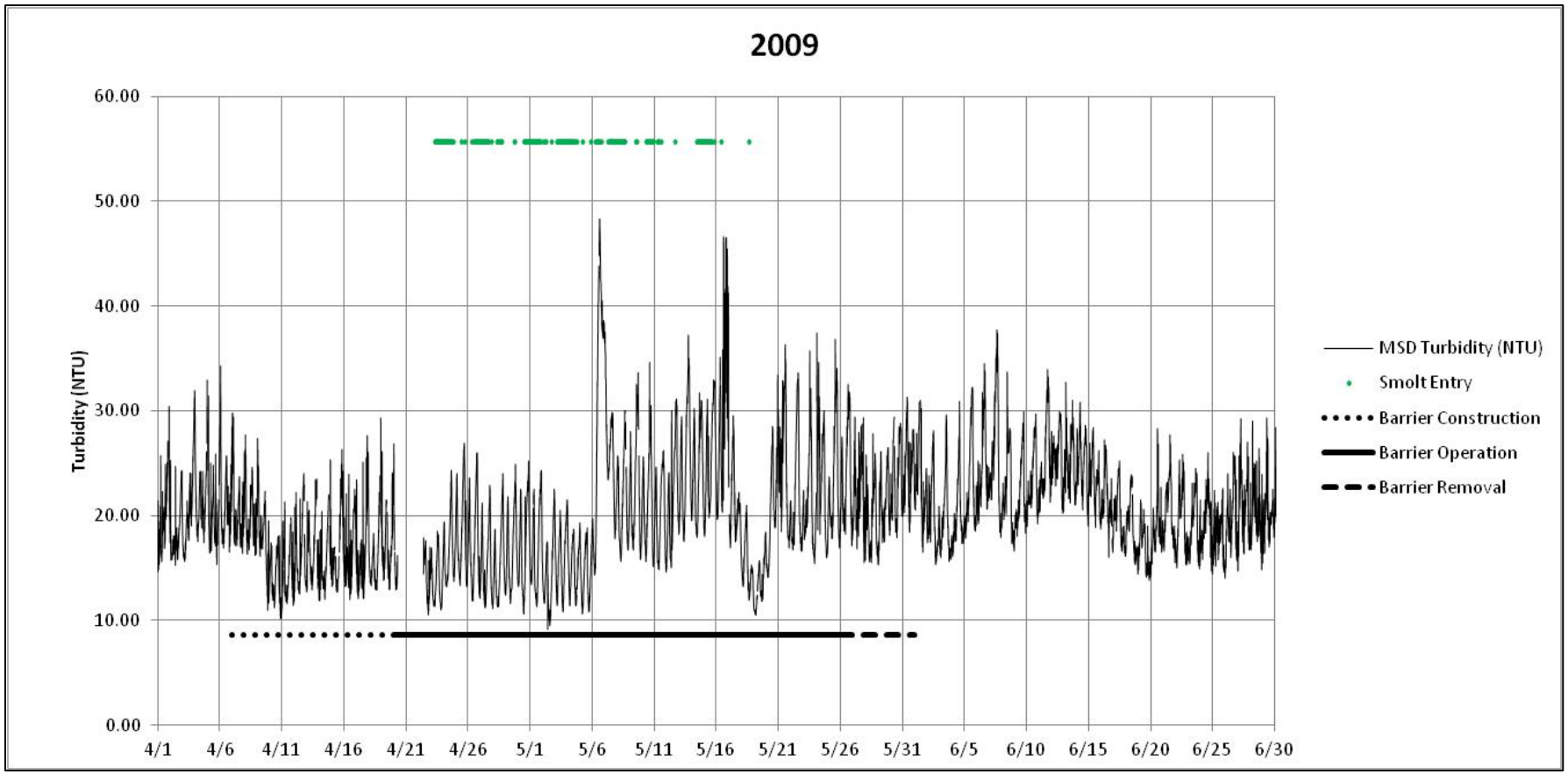
3.4.2 2010 TURBIDITY

From April 1 through June 30, 2010, the turbidity at the MSD gauge ranged from 12.1 to 42.9 NTU (Figure 3-30). When tagged juvenile Chinook salmon were recorded by the receivers, the mean turbidity in 2010 was higher than in any other year (Table 3-5; Figures 3-29, 3-30, 3-31, and 3-32). The turbidity also was the least variable in 2010 (Table 3-5; Figure 3-28).



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

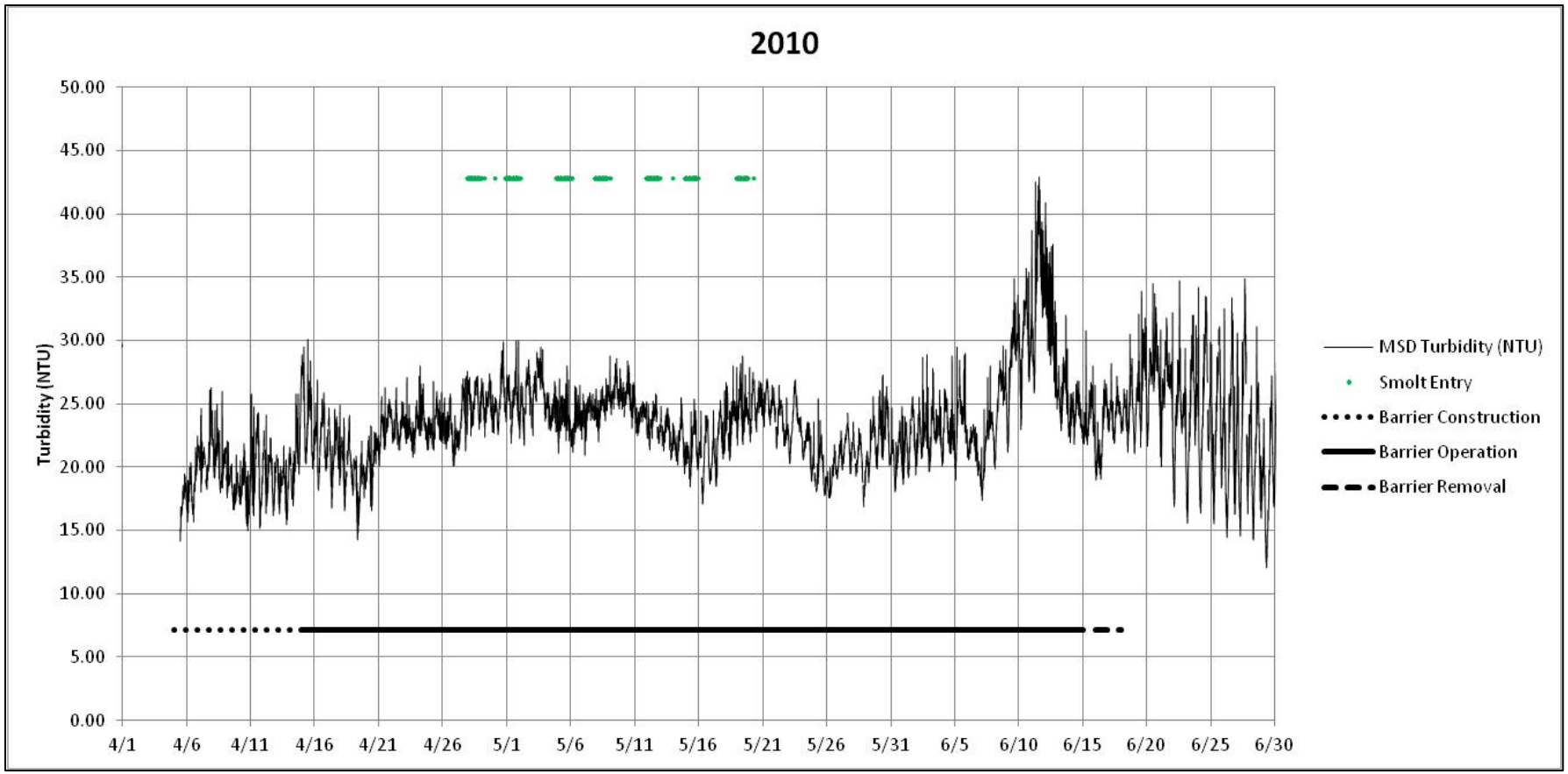
Figure 3-28 **Daily Mean Turbidity in the San Joaquin River at Mossdale (MSD), 4/1 to 6/30, 2009–2012**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: The barrier referred to in the legend was a non-physical fish barrier called a BAFF (Fish Guidance Systems Ltd, Southampton, UK). Barrier operation was not continuous, with the BAFF off approximately 50% of the time during the period of BAFF operation.

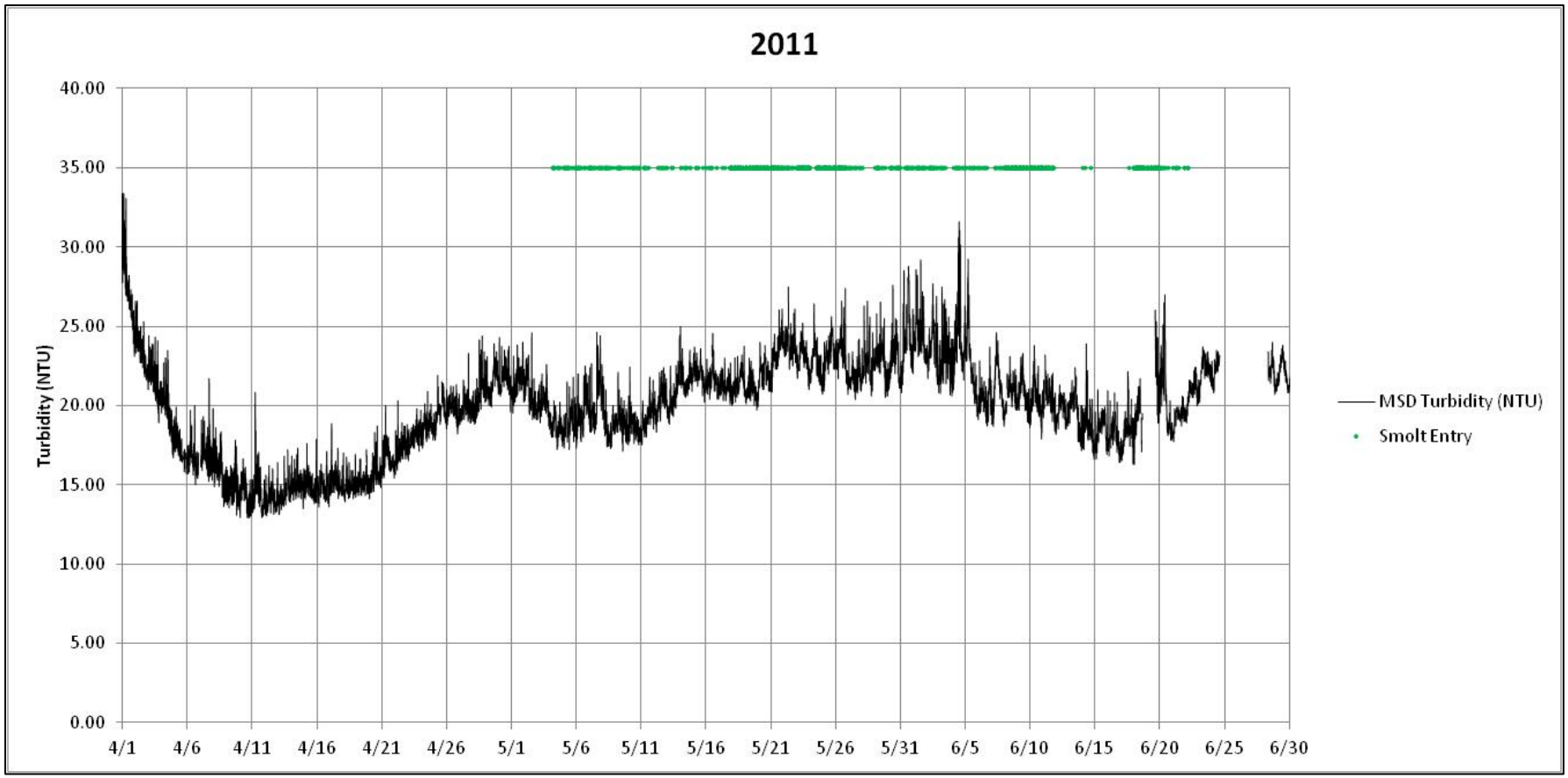
Figure 3-29 **Turbidity of the San Joaquin River at the Mossdale Gauge from 4/1/09 through 6/30/09 and Tagged Juvenile Chinook Salmon Presence**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: The barrier referred to in the legend was a non-physical fish barrier called a BAFF (Fish Guidance Systems Ltd, Southampton, UK). Barrier operation was not continuous, with the BAFF off approximately 50% of the time during the period of BAFF operation.

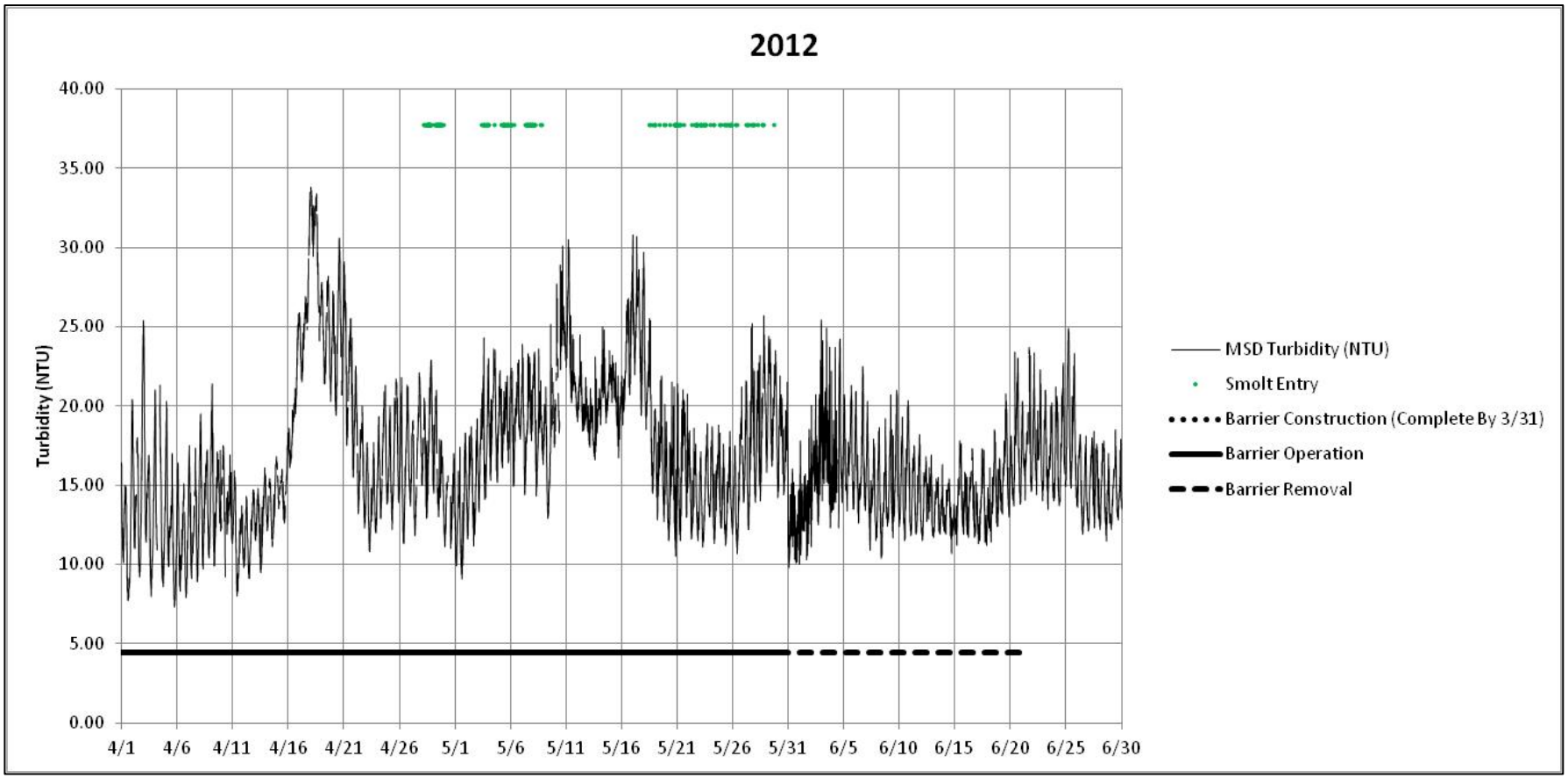
Figure 3-30 **Turbidity of the San Joaquin River at the Mossdale Gauge from 4/1/10 through 6/30/10 and Tagged Juvenile Chinook Salmon Presence**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: No barrier was installed or operated during this period.

Figure 3-31 **Turbidity of the San Joaquin River at the Mossdale Gauge from 4/1/11 through 6/30/11 and Tagged Juvenile Chinook Salmon and Steelhead Presence**



Sources: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Note: The barrier installed was a rock barrier with eight culverts.

Figure 3-32 **Turbidity of the San Joaquin River at the Mossdale Gauge from 4/1/12 through 6/30/12 and Tagged Juvenile Chinook Salmon and Steelhead Presence**

Table 3-5
Descriptive Statistics for 2009–2012 Turbidity at the MSD Gauge

Year	First Fish[1]	Last Fish[2]	MSD Turbidity (NTU)				
			Mean	Standard Deviation	Minimum	Maximum	Count
2009	4/23/09 8:24	5/18/09 13:48	19.9	6.6	9.1	48.3	2405
2010	4/27/10 22:25	5/20/10 5:54	24.1	1.9	17.1	30.0	2073
2011	5/4/11 2:51	6/22/11 4:24	21.1	2.1	16.3	31.6	4523
2012	4/28/12 4:13	5/29/12 16:35	18.0	3.8	9.1	30.8	2945

Notes: MSD = San Joaquin River at Mossdale; NTU = Nephelometric Turbidity Units

[1] Date/time when the first tagged salmonids was nearest the BAFF line.

[2] Date/time the last tagged salmonids was nearest the BAFF line.

Source: Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

3.4.3 2011 TURBIDITY

From April 1 through June 30, 2011, the turbidity at the MSD gauge ranged from 12.9 to 33.4 NTU (Figure 3-31). When tagged juvenile Chinook salmon and steelhead were present, the mean turbidity in 2011 generally was lower than in 2010, but was similar to 2009 turbidity (Table 3-5; Figures 3-28, 3-29, 3-30, and 3-31). The standard deviation in turbidity was similar in 2010 and 2011, and both of these years exhibited lower standard deviation than in other years (Table 3-5).

3.4.4 2012 TURBIDITY

From April 1 through June 30, 2012, the turbidity at the MSD gauge ranged from 7.3 to 33.8 NTU (Figure 3-32). Furthermore, in this same period, the mean turbidity was 16.6 NTU, the lowest recorded mean for the 4 years studied (Figure 3-28). The turbidities from April 1, 2012, until fish were released on April 28, 2012, represented the lowest turbidity of any 4-week period in the 4 years studied. In addition, when tagged juvenile Chinook salmon and steelhead were present, the mean turbidity in 2012 was lower than in than any other year (Table 3-5; Figures 3-29, 3-30, 3-31, and 3-32). Only 2009 exhibited a higher standard deviation in turbidity than 2012 while tagged juvenile Chinook salmon and steelhead were released (Table 3-5).

4 BARRIER TREATMENTS

4.1 NON-PHYSICAL BARRIER: THE BIO-ACOUSTIC FISH FENCE (BAFF)

Installation of the spring rock barrier has been controversial because of the area of habitat impacted and its potential effects on the risk of entrainment into the SWP and CVP export facilities for delta smelt, a species that is listed under the federal and California endangered species acts (see Section B.2.1 in Appendix B, "Focal Fish Species Information"). In 2008, a court order designed to protect delta smelt prohibited the installation of the spring rock barrier pending fishery agency actions or further order of the court. Subsequently, the U.S. Fish and Wildlife Service (USFWS) issued a BO for delta smelt and its critical habitat for the OCAP (USFWS 2008). USFWS determined that, as a result of its influence on the hydrodynamics of the Delta, the rock barrier potentially increases the vulnerability of delta smelt, particularly larvae and juveniles, to entrainment at CVP and SWP south Delta export facilities.

When the rock barrier is in place, a proportion of the water that would ordinarily flow down Old River is forced to flow down the San Joaquin River which benefits outmigrating juvenile salmonids. However, the rock barrier can also cause or augment net flow reversal in Old River. In addition, the barrier increases flows in Turner and Columbia cuts, two major central Delta channels that flow toward the south Delta. The result of these hydrodynamic changes is an increase in reverse flow in several channels, which has been noted to have coincided with increases in salvage of delta smelt (e.g., in 1996) (Nobriga et al. 2000). Therefore, DWR proposed use of a BAFF as an option at the HOR to meet the objective of excluding outmigrating salmonid juveniles from Old River while also minimizing the potential effects to delta smelt and Delta hydrodynamics. The BAFF allowed unobstructed flows into Old River, thus helping to lessen reverse flows in Old River as a result of SWP/CVP exports.

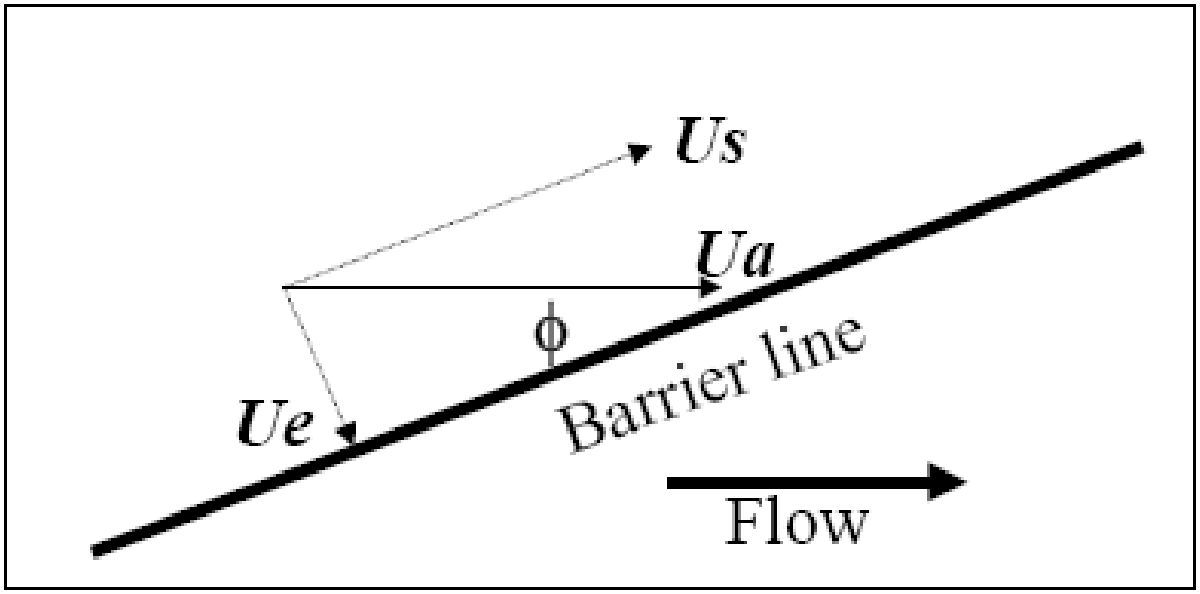
The BAFF is a multi-stimulus fish barrier that combines strobe lights, an air bubble curtain, and sound at frequencies and levels repellent to fish. The BAFF is intended to form a behavioral deterrent for juvenile salmonids in the San Joaquin River, rather than a physical barrier (e.g., rock barrier), to prevent entry into Old River. The sound system and strobe light flash rate can be tuned to known sensitivities of various fish species. Studies with Chinook salmon and delta smelt have shown that when the sound and strobe light flash rate are tuned according to these species' sensitivities, the barrier was effective as a deterrent for juvenile Chinook salmon (Bowen et al. 2009) and delta smelt (Bowen et al. 2010). The sound frequency range used was 50 to 600 Hertz (Hz). Audiogram studies (Oxman et al. 2007) have shown maximum hearing sensitivity at around 250 Hz for juvenile Chinook salmon. The BAFF's strobe lights flashed at 360 flashes per minute. Nemeth and Anderson's (1992) data showed a strong reaction to strobe lights at this flash rate.

Although future minor design adjustments may occur based on the 2010 design, the BAFF is 138 m long and made up of 17 separate 7.9-m sections. The barrier frame includes 64 Fish Guidance Systems Model 15-100 sound projectors, spaced approximately 2.0 m apart; 136 strobe lights (Fish Guidance Systems 100-centimeter-linear intense modulated lights [IMLs]), and perforated pipe. The sound projectors are driven by a signal generator (Fish Guidance Systems Model 1-08) and eight Fish Guidance Systems Model 400 power amplifier/control units, located in an onshore building. The strobe lights are powered from a "power supply accumulator," a unit that accumulates energy until it is discharged to the IML, positioned every 12 strobe lights; the flash rate is triggered from the Model 1-08 signal generator. The exact power rating for the IMLs and the

wavelength of the light are proprietary (Fish Guidance Systems Ltd, Southampton, UK). However, on visual inspection at the barrier study area under low-light conditions, the IMLs could be detected, flashing in the water at a maximum of 10 m distance from the BAFF. This led to the 10-m line, developed under low-light conditions; it was assumed that if a human eye could perceive the IML at 10 m, then a juvenile Chinook salmon would definitely experience the IML at less than or equal to 10 m from the BAFF.

The barrier is positioned diagonally across the main river channel, upstream of the divergence, and is aligned to guide outmigrating juvenile Chinook salmon to the San Joaquin River (Figure 2-4, "Barrier Alignments near the Head of Old River, 2009–2012," in Chapter 2, "Study Area and Focal Fish Species"). In designing the barrier, the flow was assumed to split 50/50 at the divergence, and the streamlines were assumed to divide midway across the river. Therefore, the angled barrier was designed so that fish present in streamlines that were entering Old River would be guided into streamlines entering the San Joaquin River. Thus, the barrier was planned to extend from the left bank (Old River side) to beyond the mid-channel position upstream of the divergence (Figure 2-4 in Chapter 2).

The diagonal fish screen/barrier concept is well known (Turnpenny and O'Keeffe 2005). The velocity perpendicular to the barrier line must be kept at or below the maximum sustainable swimming speed of the fish. In 2009, during BAFF design, the critical swimming speed (U-crit) was estimated from swimming performance data given by Muir et al. (1993: Figure 3), who give a U-crit range of 3.4 to 3.9 body lengths per second (BL/s). For design purposes, a value of 3.4 BL/s was assumed. The smallest size of fish desirable to protect was assumed to be 58 mm FL based on the minimum of length range for juvenile Chinook salmon (58 to 100 mm FL) expected in the south Delta, reflecting salvage data at the Tracy Fish Collection Facility and the Skinner Fish Protection Facility (NMFS 2013). This gave a conservative design figure for escape velocity (*Ue*) of 0.2 m/s (Figure 4-1).



Note: Ua = main channel velocity; Ue = fish escape velocity; Us = sweeping velocity component along the face of the screen
Source: Turnpenny and O'Keeffe 2005

Figure 4-1 **Flow Velocity Components in Front of an Angled Fish Barrier**

Figure 4-1 shows the relevant velocity components for an angled fish barrier. The main channel velocity is denoted *Ua*. The velocity perpendicular to the screen face is the fish escape velocity, *Ue.* For a barrier angle φ, this is calculated as Equation 4-1:

$$Ue = Ua \sin \varphi$$

The sweeping velocity, *Us*, is the component parallel to the screen face. This can be used to calculate the time taken for the fish to traverse the screen from any given point when swimming at velocity *Ue*. It is calculated as Equation 4-2:

$$Us = Ua \cos \varphi$$

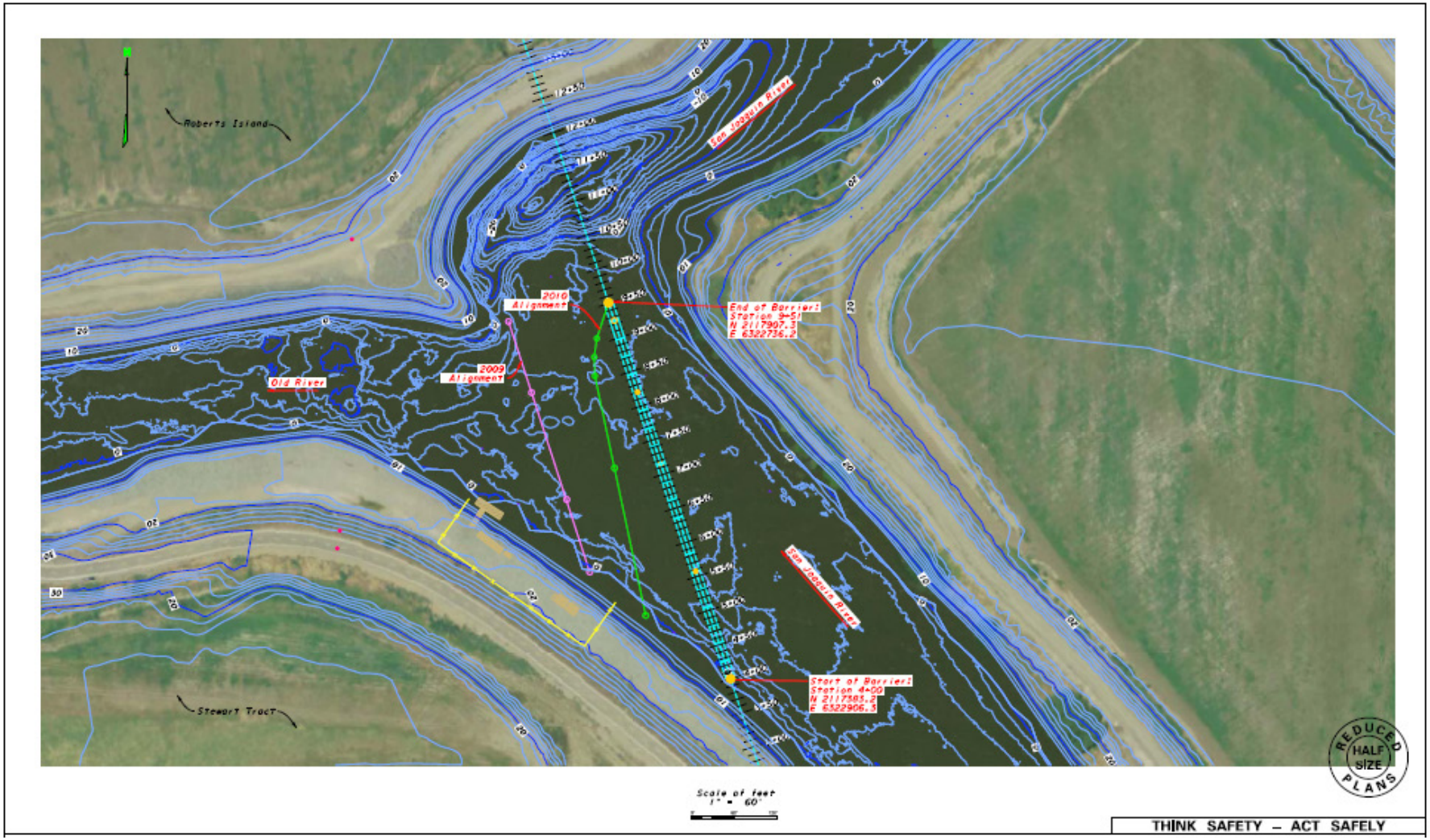
The BAFF design for the barrier study area was based on the following values:

- River width at barrier line equaled 91 m;
- Average velocity (data from the MSD gauge, approximately 4.5 km upstream of HOR junction) was 0.41 m/s. Therefore, the average velocity used for the design was 0.5 m/s. This value was slightly larger than the observed mean to provide a safety margin; and
- River depth along barrier line exhibited a maximum of 4.5 m, and averaged approximately 2.5 m.

To achieve *Ue* = 0.20 m/s perpendicular to the barrier, the barrier angle φ was arcsin (0.2/0.5) equals 24°. This is the angle relative to the centerline of the river flow at the upstream point of the barrier. This was the angle, 24°, of the BAFF as deployed in 2009 (Figure 4-2).

In 2010, the barrier length was increased from 114 m to 138 m to reduce the risk of diverting fish into the deep scour hole in the concave bend of the San Joaquin River limb at the HOR study area. Also, the angle of the BAFF incident to the left (west) bank was increased to 27° to allow more distance between a deterred juvenile Chinook salmon and the scour hole. Additionally, a "hockey-stick" bend was shaped toward the tip of the barrier, made up of the last four barrier units; this was angled at 30° to the main barrier angle. This bend was intended to deter juvenile Chinook salmon away from the deep scour hole, where predation events were observed in 2009. The alignment of the 2010 BAFF barrier is shown in Figure 4-2.

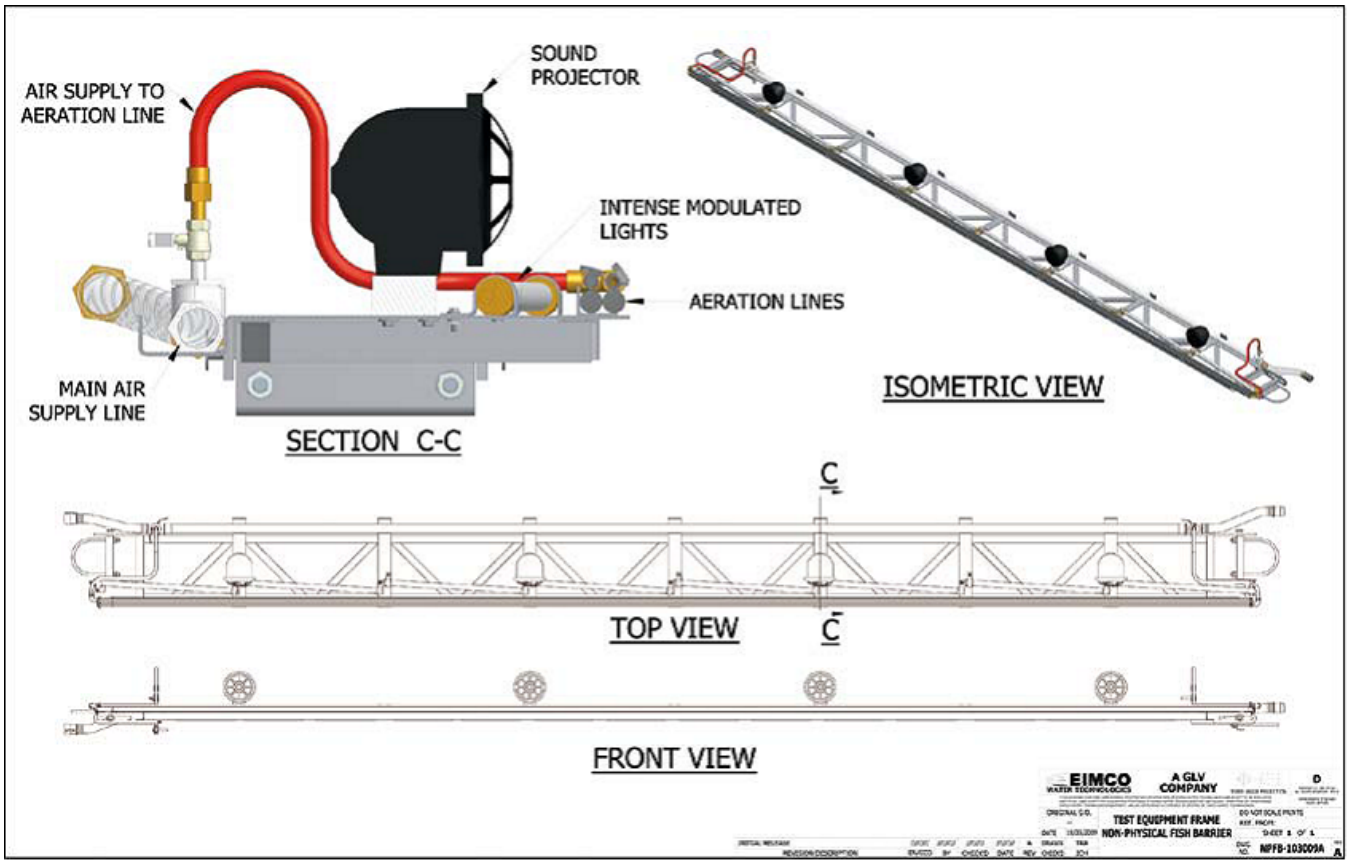
Consideration was given to two methods of barrier deployment: either suspending the barrier from the surface or mounting it rigidly on the riverbed. Surface mounting is simpler for a temporary barrier but less robust. Owing to the risk of high flows and debris, bed mounting was selected. The San Joaquin River could provide habitat for the protected green sturgeon (see Chapter 2, "Study Area and Focal Fish Species"), and a condition of permitting the installation was that a gap of 0.46 m should be left below the barrier infrastructure to allow sturgeon to pass. This was achieved by supporting the BAFF chassis with piles inserted for this purpose. This also facilitated free bedload movement and reduced the risk of equipment becoming inundated by fine sediments. The resulting gap below the BAFF meant that approximately 18% of the cross-sectional area of the barrier channel was not "screened" by the BAFF.



Source: DWR 2013

Figure 4-2 **Plan View of the Head of Old River Divergence (BAFF line in 2009 shown by pink line and in 2010 by green line)**

Each of the 7.9-m sections had adjustable height pivots to provide flexibility in lowering or raising each section to follow the riverbed contour. The barrier frame was supported by up to four piles in the river channel. Additionally, concrete piers were placed to support the frame above the riverbed in several locations so that the system would not move out of alignment and would allow for vertical adjustment of the barrier relative to the riverbed or water surface (Figure 4-3).



Source: Data provided by EIMCO

Figure 4-3 **Schematic of the Lattice Construction of the Barrier Support Frames (with sound projectors, strobes, and aeration lines)**

The air bubble curtain was generated by passing air (approximately 16.4 cubic meters per minute) through a uniformly perforated pipe attached to the barrier frame. The air was supplied by a trailer-mounted air compressor capable of an operating pressure up to 7 bar, although the actual operating pressure was lower, typically 2 to 3 bar. The air pipe was a rubberized construction, allowing the pores to open under pressure and self-seal when the air flow stopped. The primary function of the bubble curtain was to contain the sound that was generated by the sound projectors. The air bubble/water mixture acted as a pseudo-medium in which sound would travel at a velocity intermediate between that of air and water alone. Essentially, the sound was refracted and became encapsulated within the bubble curtain, which allowed a precise linear wall of sound to be developed (Bowen et al. 2009). Sound levels decayed very rapidly in the water outside of the bubble curtain, dropping to a few percent of the sound projector level within 3 m (Bowen et al. 2012: Appendix A). This led to the development of the 3-m line; a juvenile Chinook salmon would definitely experience the sound deterrent when it passed within 3 m of the BAFF. Therefore, during the day, a 3-m line was established, and at night a 10-m line was established (see

Section 5.2.2, “Calculation of Barrier Deterrence Efficiency”). These lines were used to determine if a tagged salmonid “experienced” the BAFF; if the tagged individual passed within 3 m of the BAFF during the day, or within 10 m at night, it was determined to have “experienced” the BAFF.

Up to 120 amps (115 volts, alternating current) of an inductively rated power supply was required to run the complete light and sound generating system. A small trailer housed the control units, signal generators, and amplifiers, because these units had to be kept dry.

4.2 HEAD OF OLD RIVER PHYSICAL ROCK BARRIER

The rock barrier is installed biannually, in spring and fall. The spring rock barrier is intended to prevent downstream-migrating juvenile salmonids in the San Joaquin River from entering Old River and, thereby, avoiding their exposure to SWP and CVP diversion operations and unscreened agricultural diversions. The spring rock barrier is constructed with approximately 9,560 cubic meters of rock to form a 68.5-meter-long by 25.9-meter-wide (at the base) berm. The spring rock barrier has a crest elevation of +3.8 m North American Vertical Datum of 1988 (NAVD) (Figure 4-4). The south end of this barrier has eight 1.2-meter-diameter culverts with slide-gates built into the barrier abutment, and a 22.9-m clay weir at an elevation of +2.5 m NAVD. Unlike the Old River at Tracy and Grant Line Canal barriers, no boat portage facility exists at this barrier.

The fall rock barrier is similar in design to the spring rock barrier, but smaller. The fall rock barrier is intended to benefit migrating adult salmon in the San Joaquin River by improving flow and dissolved oxygen conditions. The fall rock barrier has six 1.2-m culverts with slide-gates and a 6.1-m weir section at an elevation of +0.7 m NAVD. It is approximately 68.5 m long by 16.8 m wide at the base, and has a crest elevation of +2.5 m NAVD. The fall rock barrier is composed of approximately 5,730 cubic meters of rock.



Source: DWR 2013 and AECOM 2013

Figure 4-4 **Physical Rock Barrier at the Head of Old River with Eight Culverts in 2012**

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5 METHODS

5.1 ANALYSIS OF TAGGED JUVENILE SALMONIDS

5.1.1 FATE OF TAGGED JUVENILE SALMONIDS

The analysis of tagged juvenile Chinook salmon and steelhead followed the methodology used for the 2011 analysis of the effects of a non-physical barrier at Georgiana Slough (DWR 2012). Acoustic transmitters were originally inserted in juvenile salmonids in accordance with the Vernalis Adaptive Management Program (VAMP) (SJRGA 1999, 2010, 2011, and 2013) and the Six-Year Steelhead Study (6YSS) (NMFS 2009; SJRGA 2013) by the VAMP/6YSS team. The fates of the tagged fish were classified as follows:

1. Released but never arrived;
2. San Joaquin River;
3. Old River;
4. Predation; or
5. Unknown.

These fates were used to estimate O_E, P_E, and D_E. These three metrics (O_E, P_E, and D_E) were evaluated through samples of tagged juvenile salmonid as they arrived at the HOR study area. If a tagged juvenile salmonid was determined to have been eaten, then that tag was evaluated in an analysis of proportion eaten. The possible errors that could have been made in determining the fate of being eaten are assessed for implications with respect to the proposed recommendations (Section 8.2.1, "Further Examine Predation Classification").

From 2009 through 2012, there were two types of acoustic telemetry gear used for evaluations of movement and behavior of acoustic tags: HTI and VEMCO. HTI gear provided sub-meter positioning and was used to evaluate behavior in the vicinity of the barrier location; this was the primary gear used in the analyses presented in this report. VEMCO gear provided one-dimensional information and collected route selection information and overall barrier effectiveness measures in 2012. Analyses related to VEMCO gear are presented in Appendix C, "Comparisons of HTI and VEMCO Data."

5.1.2 STUDY FISH SOURCES AND TAG SPECIFICATIONS

HTI EQUIPMENT

Three hatchery sources were used to provide juvenile Chinook salmon and steelhead for the study during the four study years, as shown in Table 5-1. For Chinook salmon, the Feather River Fish Hatchery and the Merced River Fish Hatchery supplied fish. All steelhead were from the Mokelumne River Fish Hatchery.

Table 5-1
Juvenile Salmonids Used for Head of Old River Barrier Evaluations Using HTI Gear

Study Year	Species	Fish Hatchery	Run	Total Number Released	Minimum Size (mm FL)	Maximum Size (mm FL)
2009	Chinook Salmon	Feather River	Fall-Spring Hybrid	933	80	110
2010	Chinook Salmon	Merced River	Fall	504	99	121
2011	Chinook Salmon	Merced River	Fall	1,915	94	140
2011	Steelhead	Mokelumne River	Winter	2,208	149	396
2012	Chinook Salmon	Merced River	Fall	424	95	135
2012	Steelhead	Mokelumne River	Winter	16	167	269

Notes: FL = fork length; mm = millimeter
Sources: SJRGA 2010, 2011, 2013

The Chinook pre-smolts and smolts (referred to as "juveniles" in this report) from the Feather River and Merced River fish hatcheries for this study mimicked the ocean-type life history pattern (described in Appendix B, "Focal Fish Species Information"). These two hatcheries take ocean-type adults, spawn them between September and January, house the fry (30 to 55 mm TL) in raceways, where they are maintained for several months. At the Feather River Fish Hatchery, the target size is 96 mm TL by April (Kastner, pers. comm., 2013). At the Merced River Fish Hatchery, the target is to maximize growth by feeding approximately 3.5% of body weight per day (Kollenborn, pers. comm., 2013). The fry become parr in a few months and eventually begin to undergo the physiological and behavioral changes of smoltification. The ocean-type parr begin to smoltify in March or April. The largest individuals, a minimum of 102 mm TL, were selected in April for use in the study. These juveniles may be considered pre-smolt or smolt, depending on the state of smoltification in each individual. These juveniles were produced in the hatchery and used as surrogates for naturally produced (wild) juveniles. Chinook juveniles were surgically implanted with acoustic transmitters and released in the San Joaquin River 24.4 km upstream of the HOR study area.

In 2009, the HTI Model 795 *Lm* acoustic transmitter ranged in mass from 0.62 to 0.69 grams (in air) and were surgically inserted into the coelomic cavity of the juvenile Chinook salmon (Table 5-2). The target tag burden (i.e., tag:body mass ratio) of 5% (as recommended by Liedtke et al. 2012) was exceeded in 98% of cases (Table 5-3). The high number of exceptions existed because the spring/fall hybrids from the Feather River Fish Hatchery grew more slowly than expected once they were transferred to the Merced River Fish Hatchery (SJRGA 2010). From 2010 through 2012, juvenile Chinook salmon supplied for tagging were larger (Table 5-1) and the target tag burden was reduced and exceeded in 5.3 to 11% of the juvenile Chinook salmon tagged (Table 5-3).

Table 5-2
Acoustic Tag Models and Specifications Used in the Head of Old River Studies from 2009–2012

Study Year	Tag Model Number	Quantity Used	Diameter (millimeters)	Length (millimeters)	Mass in Air Mean (grams)	Used for Sampling
2009	795*Lm*	950	6.8	16.5	0.65	Juvenile Chinook Salmon
2010	795*Lm*	508	6.8	16.5	0.65	Juvenile Chinook Salmon
2011	795*Lm*	1,089	6.8	16.5	0.65	Juvenile Chinook Salmon
	795*LD*	540	6.8	21.0	1.0	Juvenile Steelhead
	795*LX*	36	16	45.0	13.0	Predator Species
	795*LG*	13	11	25.0	4.5	Predator Species
2012	M800	76	6.7	16.4	0.50	Juvenile Chinook Salmon
	795*Lm*	348	6.8	16.5	0.65	Juvenile Chinook Salmon
	795*LD*	16	6.8	21.0	1.0	Juvenile Steelhead
	795*LX*	3	16.0	45.0	13.0	Predator Species
	795*LG*	45	11.0	25.0	4.5	Predator Species

Source: Data compiled by AECOM and Turnpenny Horsfield Associates in 2013.

Table 5-3
Range of HTI Tag Burdens Experienced by Salmonid Juveniles in 2009–2012

Study Year	Tag Model Number	Minimum Tag Burden	Mean Tag Burden	Maximum Tag Burden	Percentage of Tags Exceeding 5% of Body Mass	Species
2009	795*Lm*	0.044	0.071	0.102	98.0	Chinook Salmon
2010	795*Lm*	0.028	0.042	0.058	6.8	Chinook Salmon
2011	795*Lm*	0.020	0.041	0.065	11.0	Chinook Salmon
2012	M800	0.022	0.039	0.054	5.3	Chinook Salmon
2012	795*Lm*	0.020	0.039	0.124	6.6	Chinook Salmon
2012	795*LD*	0.004	0.006	0.008	0.0	Steelhead

Source: Data compiled by AECOM and Turnpenny Horsfield Associates in 2013.

5.1.3 SURGICAL, HANDLING, AND RELEASE METHODS

The barrier effectiveness evaluations described in this report were conducted as part of a coordinated suite of studies in the south Delta, which included the VAMP (SJRGA 1999) and the 6YSS (NMFS 2009; SJRGA 2013). The coordinated studies relied on one husbandry team (VAMP/6YSS) to conduct the surgical implantation, transport of the fish to the release site (i.e., Durham Ferry for all years, 2009 through 2012), handling of the fish to minimize effects on behavior and health, and release of the tagged juveniles according to the agreed schedule.

Concept guidelines important to the tag implantation procedures for HTI and VEMCO tags are described by Adams et al. (1998) and Martinelli et al. (1998). These guidelines were used to develop the methodologies

employed in these coordinated studies (this study, VAMP [SJRGA 1999; SJRGA 2010, 2011, and 2013], and 6YSS [NMFS 2009; SJRGA 2013]); the south Delta applications for surgery, handling, and release were described in general by Liedtke et al. (2012) and specifically for each year: 2009 (SJRGA 2010), 2010 (SJRGA 2011), 2011 (SJRGA 2013), and 2012 (J. Israel, pers. comm., 2013). For 2011, the methodology describing the specifics of surgical implantation, handling, and release can be evaluated in SJRGA (2013). For the 2012 methodology, Israel (pers. comm., 2013) reported that methods varied in only minor details from SJRGA (2013).

For tagged juvenile Chinook salmon, the 2009 releases were executed earlier than any other year, with an initial release of April 22, 2009, and initial arrival at the HOR study area on April 23, 2009 (an arrival onset 4 to 11 days earlier than other years) (Table 5-4). In contrast, the 2011 tagged juvenile releases were executed later than any other year, with the initial release of May 17, 2011, later by 22 to 26 days.

Table 5-4
Release and Detection Dates for Tagged Juvenile Salmonid Releases Used in the Studies

Year	Species	First Release[1]	First Fish[2]	Last Release[3]	Last Fish[4]
2009	Chinook Salmon	4/22/2009, 17:05	4/23/2009, 8:24	5/13/2009, 21:38	5/18/2009, 13:48
2010	Chinook Salmon	4/27/2010, 14:02	4/27/2010, 22:25	5/19/2010, 08:00	5/20/10, 5:54
2011	Chinook Salmon	5/17/2011, 15:00	5/17/2011, 21:24:47	6/19/2011, 12:00	6/22/2011, 4:24
2011	Steelhead	3/22/2011, 15:00[5]	5/4/2011, 02:51:51	6/18/2011, 0:00	6/22/2011, 04:24:00
2012	Chinook Salmon	4/26/2012, 13:00	4/28/2012, 4:13	5/27/2012, 05:00	5/29/2012, 16:35
2012	Steelhead	5/22/2012, 23:00	5/23/2012, 23:38:44	5/22/2012, 23:00	5/28/2012, 15:56:39

Notes: BAFF = bio-acoustic fish fence.
1 First Release is the date/time the first fish went in the water at Durham Ferry.
2 First Fish is the date/time when the first tagged fish was nearest the 2009 (2009 data) or 2010 (2010–2012 data) BAFF line and detected by the HOR study area hydrophone array.
3 Last Release is the date/time the last fish went in the water at Durham Ferry.
4 Last Fish is the date/time the last tagged fish was nearest the 2009 (2009 data) or 2010 (2010–2012 data) BAFF line.
5 The hydrophone array at the HOR study area was not operational between 3/22/11 and 4/5/11.
Sources: Johnston, pers. comm., 2013; SJRGA 2010, 2011, and 2013

5.1.4 ACOUSTIC TELEMETRY ASSESSMENTS

HTI HYDROPHONE DEPLOYMENT

Hydrophone arrays allowing 2D tracking of tagged fish were installed at the HOR study area from 2009 through 2012. A hand-held global positioning system (GPS) (precision level 2 to 3 m) was used to deploy each hydrophone at the appropriate location and to measure the Universal Transverse Mercator (UTM) coordinates for each hydrophone in the array. Once all hydrophones were in place, a procedure was performed to fine-tune the measured locations. This procedure used the transmitting capability of each hydrophone to produce a signal that all other hydrophones received. By measuring the time delay between the signal of the transmitting hydrophone and the signal arriving at each receiving hydrophone, the location of each hydrophone could be adjusted to fit all other time delays from all other hydrophones. In addition, the water temperature at each hydrophone was measured at the time of signal transmission to calculate the speed of sound during the procedure. For stationary hydrophones, this process results in hydrophone position estimates that allow sub-meter accuracy for acoustic tags

located within the bounds of the array. During 2009, this procedure was performed once at the start of the monitoring period. During 2010, 2011, and 2012, the procedure was performed seven, four, and three times throughout the monitoring period, respectively.

In 2009, four hydrophones were installed around the BAFF (Figure 5-1). In 2010, eight hydrophones were installed: four located upstream and four downstream of the BAFF (Figure 5-2). In 2011, nine hydrophones were installed in approximately the same configuration as 2010, with the addition of one hydrophone deployed deep in the scour hole (Figure 5-3). For 2012, 13 hydrophones were installed around the rock barrier. Four hydrophones were located in the San Joaquin River upstream of the Old River divergence, three downstream of the divergence in the San Joaquin River, two upstream of the rock barrier in the Old River, and four downstream of the rock barrier in the Old River (Figure 5-4).



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-1 **HOR Study Area—2009 Hydrophone Array with BAFF (red line)**



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-2 **HOR Study Area—2010 Hydrophone Array with BAFF (red line)**



Source: Hydroacoustic Technology, Inc. 2013

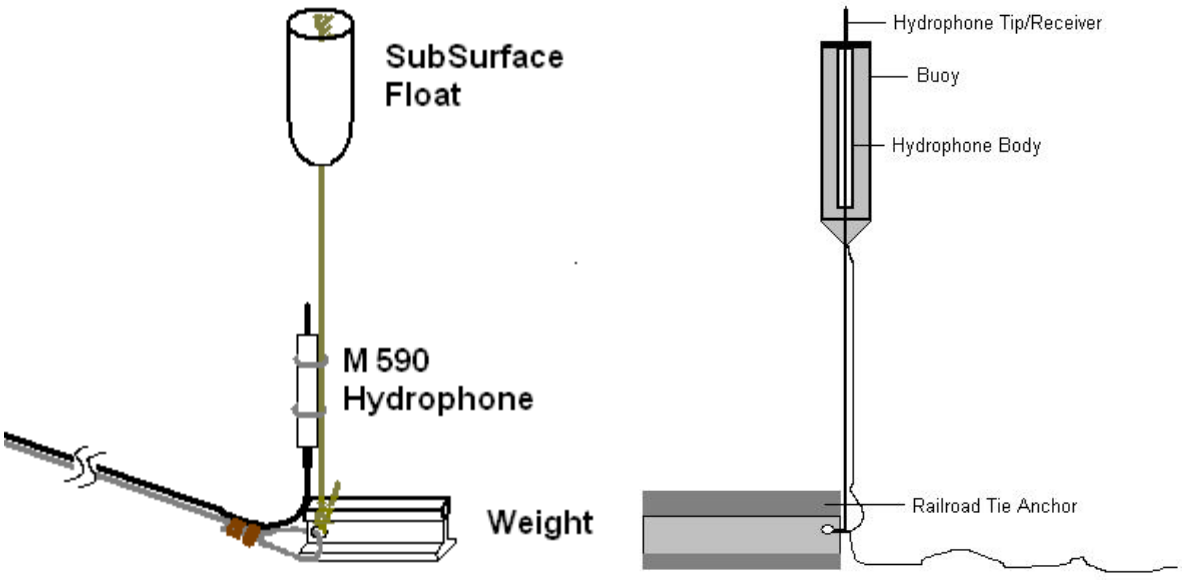
Figure 5-3 **HOR Study Area—2011 Hydrophone Array, No Barrier Treatment**



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-4 **HOR Study Area—2012 Hydrophone Array with Rock Barrier**

All hydrophones near the San Joaquin-Old River divergence were deployed using bottom mounts fabricated from a section of railroad tie as an anchor. The hydrophones were installed using tensioned aircraft cable or rope lines extending to subsurface floats (Figure 5-5).



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-5 **Conceptual Depiction of the Two Types of Hydrophone Bottom Mounts with Tensioned Lines**

HTI Acoustic Tag Specifications

HTI Model 795 and 800 acoustic tags were used for the telemetry studies conducted 2009 through 2012 at the HOR study area (Table 5-2). The tags operate at a frequency of 307 kilohertz (kHz), and were encapsulated with a nonreactive, inert, low-toxicity resin compound.

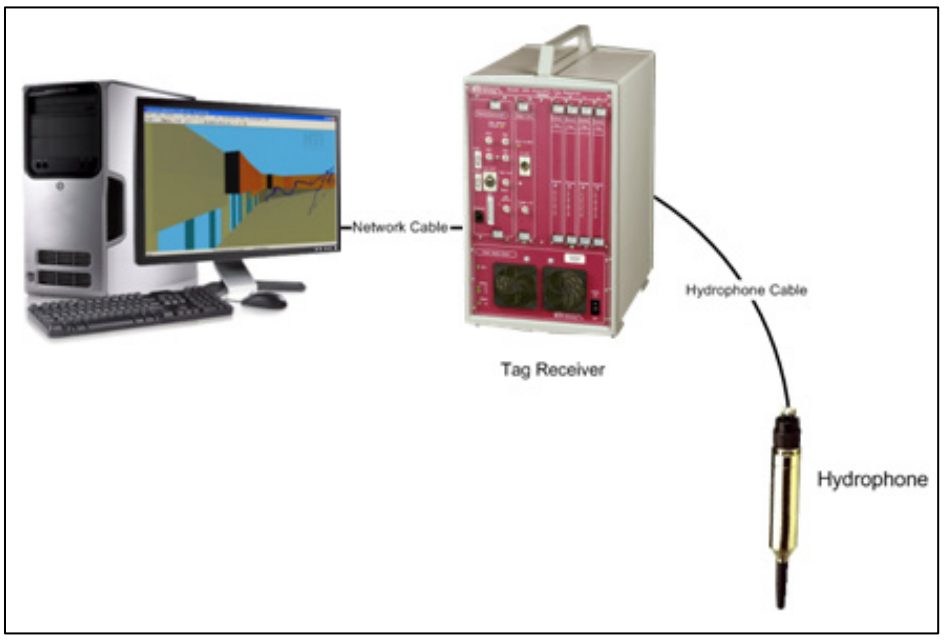
During the 2009 through 2012 study period, three different sizes of acoustic tags were used to tag juvenile Chinook salmon and steelhead, and two different sizes were used for the predator fish. Table 5-2 lists the quantity of each tag type used, with basic tag specifications, for each year of the study period.

Two-Dimensional Track Development

Data Collection

The acoustic tag tracking system consisted of acoustic tags implanted in fish, hydrophones deployed underwater, and an on-shore receiver and data storage computer. Each acoustic tag transmitted an underwater sound signal or acoustic "ping" that sent identification information about the tagged fish to the hydrophones. The hydrophones were deployed at known locations within the array to maximize spacing of the hydrophones in a 2D or 3D format. For 3D tracking, tags must be received on at least four hydrophones; for 2D tracking, tags must be received on at least three hydrophones. By comparing the time of arrival of the sound signal at multiple hydrophones, the 2D (or if the hydrophones are arranged appropriately, the 3D) position of the tagged fish can be calculated.

2D acoustic tag tracking was conducted using an HTI Model 290 Acoustic Tag Tracking System (ATTS). The primary components of the ATTS included the acoustic tag receiver, hydrophones, and a user interface/data storage computer (Figure 5-6). The system used a fixed array of underwater hydrophones to track movements of fish implanted with HTI acoustic tags.



Source: Hydroacoustic Technology, Inc. 2013

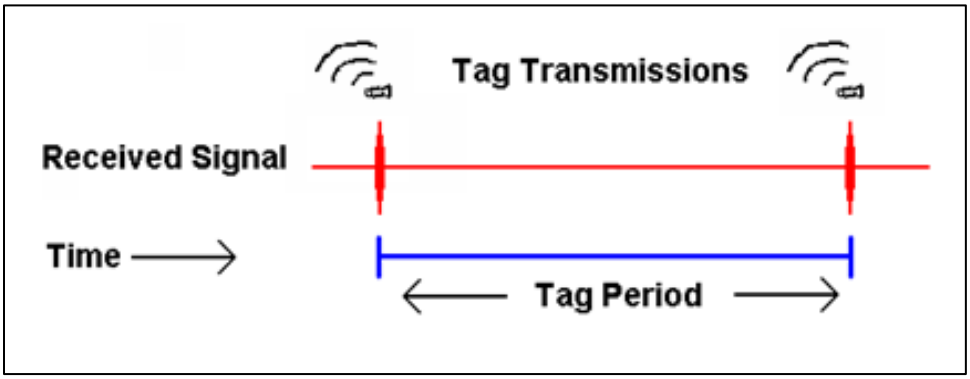
Figure 5-6 **Basic Components of the HTI Model 290 Acoustic Tag Tracking System Used to Track Movements of Fish Implanted with HTI Acoustic Tags**

As tagged fish approached the study area, the ping or signal was detected and the arrival time recorded at several hydrophones. The differences in tag signal arrival time at each hydrophone were used to calculate the 2D position of each tagged fish. The ATTS includes the following hardware and software components:

- A tag programmer that activates and programs the tag;
- Acoustic tags each transmitting a pulse of sound at regular intervals;
- Hydrophones that function like underwater microphones, listening within a defined volume of water;
- Cables connecting hydrophones to tag receivers; and
- Tag receiver that receives the tag signal from the hydrophones; conditions the signal; and, using specialized software, outputs the data into a format that is stored in computer data files.

Acoustic Tags

The HTI Model 795 acoustic tags use "pulse-rate encoding," which provides increased detection range, improves the signal-to-noise ratio and pulse-arrival resolution, and decreases position variability when compared to other types of acoustic tags (Ehrenberg and Steig 2003). Pulse-rate encoding used the interval between each transmission to detect and identify the tag (Figure 5-7). Each tag was programmed with a unique pulse-rate encoding to detect and track the behavior of individual tagged fish moving within the array.

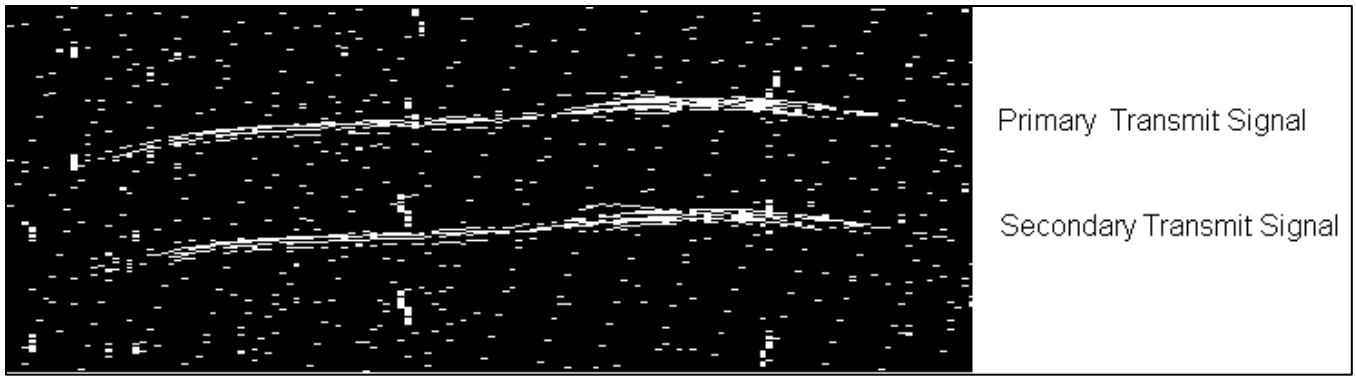


Source: Hydroacoustic Technology, Inc. 2013

Figure 5-7 **Pulse-Rate Interval Describing the Amount of Elapsed Time Between Each Primary Tag Transmission**

The pulse rate was measured from the leading edge of one pulse to the leading edge of the next pulse in sequence. By using slightly different pulse rates, tags can be uniquely identified. The timing of the start of each transmission was precisely controlled by a microprocessor within the tag. Each tag was programmed to have its own tag period to uniquely identify each tag.

In addition to the tag period, the HTI tag double-pulse mode or "subcode" option was used to increase the number of unique tag identification (ID) codes available. Using this tag coding option, each tag was programmed with a defined primary tag period and with a defined secondary transmit signal, called the subcode. This subcode defined a precise elapsed time period between the primary and secondary tag transmissions (Figure 5-8). There were 31 different subcodes possible for each tag period, resulting in more than 100,000 total unique tag ID codes.



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-8 Example Graphic from the Data Collection Program Showing the Primary (tag period) and Secondary (subcode) Transmit Signal Returns from a Model 795 Acoustic Tag

Hydrophones

The Model 590 hydrophones operate at 307 kHz and include a low-noise preamplifier and temperature sensor. Hydrophone directional coverage is approximately 330°, with equivalent sensitivity in all directions, except for a 30° limited-sensitivity cone directly behind the hydrophone where the cable is attached. The hydrophone sensor element tip is encapsulated in specially treated rubber with acoustic impedance close to that of water to ensure maximum sensitivity. The hydrophone and connector housing are made of a corrosion-resistant aluminum/bronze alloy. Specially designed cables incorporating twisted pair wire and double shields for noise reduction were used to connect each deployed hydrophone to the acoustic tag receiver.

The hydrophone preamplifier circuit provides signal conditioning and background noise filtering for transmission over long cable lengths and in acoustically noisy environments. A calibration circuit in the preamplifier provides a method for field testing hydrophone operation and was used to measure the signal time delays between hydrophones in the array. Measurement of the signal delays was used to verify the absolute position of each hydrophone within the sampling array, which is a critical part of monitoring equipment deployment. This process of measuring the hydrophone positions via the signal travel times between each hydrophone is typically referred to as the "ping-around." The Model 590 hydrophones include temperature sensors to measure water temperature at each location within the array, which was used to precisely estimate the sound velocity in water and referenced during the "ping-around" procedure.

Acoustic Tag Receiver

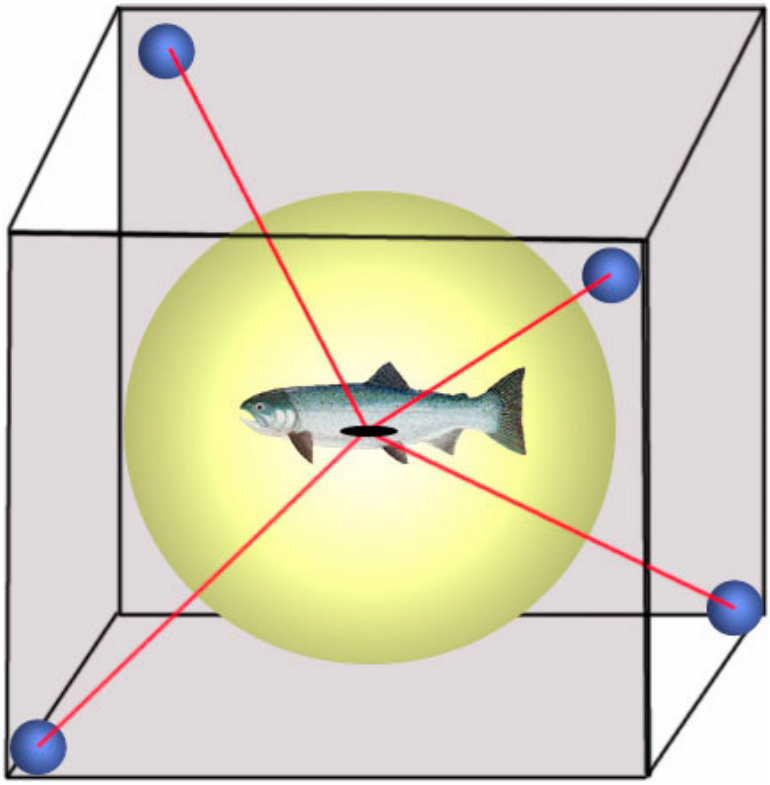
An HTI Model 290 acoustic tag receiver (ATR) can receive acoustic tag information simultaneously on up to 16 separate channels. Each ATR channel was assigned to a single hydrophone. The ATR was connected to the data collection computer, which analyzed and stored the acoustic data. An individual raw data file was automatically created for each sample hour and contained the complete set of information describing detection of each tag for all hydrophones. Data acquisition filters in the ATR were configured to identify the acoustic tag sound pulse and discriminate tag transmissions from background noise that may have been present.

The ATR pulse measurements were automatically reported for each tag signal from each hydrophone and were written to Raw Acoustic Tag (*.RAT suffix) files by the HTI acoustic tag data collection software program. Each

*.RAT file contains header information describing all data acquisition parameters, followed by the raw tag signal data. Each raw tag signal data file contains all acoustic signals detected during the time period, including signals from tagged fish and some amount of unfiltered acoustic noise, which is removed during the data analysis processes.

Mathematical Derivation of Position Calculations

Detection of a tagged fish by a single hydrophone is sufficient to confirm the presence and identity of the target, but a tag must be simultaneously detected by at least four hydrophones to be positioned in three dimensions (Figure 5-9). To be accurately positioned in two dimensions, a tag must be simultaneously detected on at least three hydrophones. 2D and 3D acoustic tag coordinates with sub-meter accuracy require accurate knowledge of the individual hydrophone positions. In addition, the hydrophones detecting the tag signal must have a direct "line of sight" path to the tag, and must be located in different vertical planes (for 3D only). As an acoustic tag is detected by three or four hydrophones that are all cabled to a single receiver, the difference in the arrival time of the transmission to each sensor was used to triangulate the exact location of the tag. HTI receivers have a built-in GPS receiver that updates to Universal Coordinated Time (UTC), so there is no clock drift. HTI receiver clock times are within 20 to 50 nanoseconds of UTC. Typically, many sequential tag positions are derived for each fish, providing a time series of locations. These positions are tracked and associated to define a swimming path for each tagged fish, which is mapped and presented in a 2D or 3D display. The underlying data are all stored for additional analyses.



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-9 Positioning of an Acoustic Tag in Three Dimensions with a Four-Hydrophone Array

The method that is used to determine acoustic tag positions by the HTI systems follows the same basic principles employed by GPS technology. The acoustic tag transmits a signal that is received by at least four hydrophones. By knowing the positions of the four hydrophones and measuring the relative signal arrival times at the hydrophones, the locations of the tagged fish can be estimated.

This process is described mathematically in the following equation. Assuming that h_{ix}, h_{iy}, h_{iz} define the x, y, z coordinate locations of the i[th] hydrophone, and F_x, F_y, F_z represent the unknown x, y, z locations of the tagged fish, the signal travel time from the tagged fish to the i[th] hydrophone, t_i, is given by:

$$t_i = \frac{1}{c}\sqrt{(h_{ix} - F_x)^2 + (h_{iy} - F_y)^2 + (h_{iz} - F_z)^2}$$

The constant "c" in the above equation defines the underwater sound velocity. This equation cannot be solved for a single hydrophone detection; however, given the three unknown fish coordinates, a solution can be determined based on the convergence of multiple hydrophone measurements. The differences between the arrival times of the signal at the multiple hydrophones ($t_i - t_j$) is described as follows:

$$t_i - t_j = \frac{1}{c}\left[\sqrt{\left(h_{ix} - F_x\right)^2 + \left(h_{iy} - F_y\right)^2 + \left(h_{iz} - F_z\right)^2} - \sqrt{\left(h_{jx} - F_x\right)^2 + \left(h_{jy} - F_y\right)^2 + \left(h_{jz} - F_z\right)^2}\right]$$

For four hydrophones, there are three such distinct signal arrival-time difference equations. The system of nonlinear equations is determined by solving the tagged fish coordinates, such that the mean squared difference between the measured (left side of the equation above) and calculated time differences (right side of the equation above) are minimized.

Individual tag positions were then assembled in chronological order to form a 2D trace representing the movement of the fish as it passed through the array. This process was done from stored arrival time data (from *.RAT files) and in real time through the acoustic tracking system.

The relatively shallow water depths present in the vicinity of the HOR study area dictated the use of a 2D tracking approach. The 2D HTI tracking algorithm requires time delays from just three hydrophones, modifying the above equation to address only the x and y dimensions. Although 3D tracking is possible in shallow water, it requires close hydrophone spacing and a large increase in the total number of hydrophones to accurately derive the depth component. 2D tracking provided the necessary fish passage and behavioral information required for the HOR study area evaluation at a lower cost than a 3D array. The HTI data collection and analysis software programs incorporated both 2D and 3D tag tracking algorithms and automatically selected the best available solutions from multiple hydrophone detections.

Data Analysis

Two separate programs were used to process acoustic tag data: AcousticTag (Version 5.00.04) and MarkTags software (HTI, Seattle, Washington). AcousticTag was used initially to acquire data from the ATR and store it in raw acoustic echoes files. MarkTags was used to read the raw acoustic echo files, identify tag signals, and create

acoustic tag files. These processed acoustic tag files were used again in AcousticTag to position the tags in 2D space.

As described previously, AcousticTag acquires data and stores it in *.RAT files. These raw echoes are not associated with any specific tag ID or spatial positioning. Depending on the project site and environmental conditions, many echoes found within these files are not tag data, but originate from secondary sources such as ambient noise or reflections from the surface or nearby structure (called multipath). Thus, the first phase of post-processing was to identify and select the acoustic echoes that were received directly from tags, and to assign the unique tag ID to these echoes.

The echo selection process was completed in the MarkTags program. The procedure for isolating the signals from a given tag follows from the method used for displaying the signals themselves. Each vertical scan in the time-scaled window shows the detected arrivals that are equal to the pulse-rate encoding of a particular tag (Ehrenberg and Steig 2003). Only signals from the tag programmed with the same period will fall along the straight line. The results of the tag selection process completed in MarkTags was written to track acoustic tag files (*.TAT file). These files contain the individual raw acoustic echoes with assigned tag ID codes, but without spatial positioning assignments.

AcousticTag was used for the triangulation calculations and to output a database of 2D coordinate locations for each fish. This program provided information describing date and time; the x, y, and z coordinates; and hydrophones used in creating the 2D track. It then recorded this information to a Microsoft® Access database file.

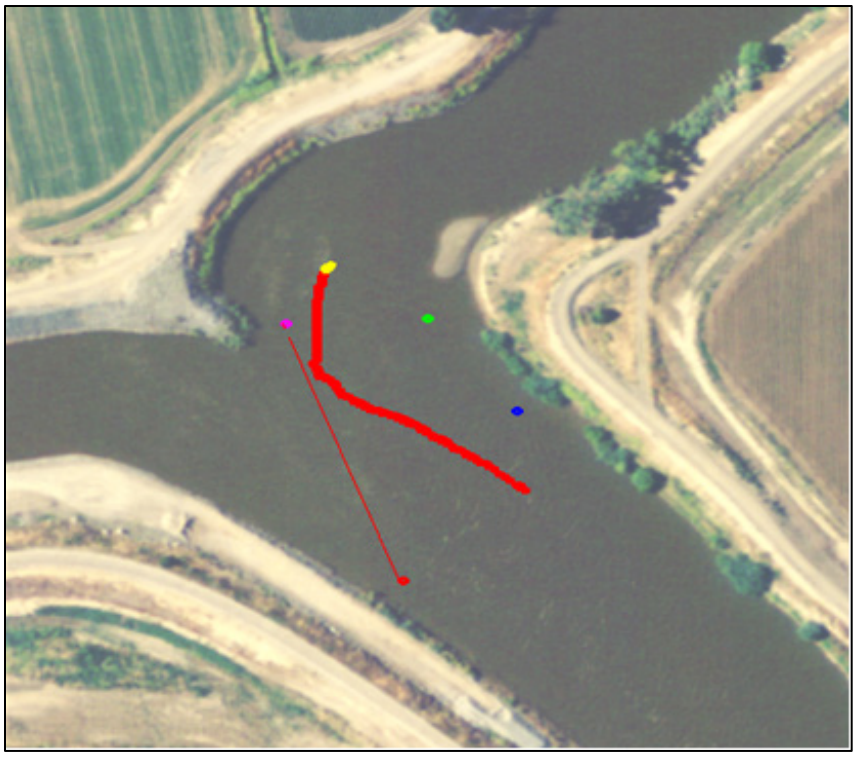
DETERRENCE AND FATE DETERMINATION GUIDELINES

Deterrence Determination from Two-Dimensional Track

For all years of the study, a hydrophone array was deployed that allowed tracks of individual fish to be developed from tag transmission data. Each individual position calculated from a single tag transmission was developed in a geo-referenced UTM coordinate system, so it could be overlaid onto a geo-referenced map of the HOR study area. The time-stamped positions for each tagged fish were assembled into a time-ordered track which could be viewed in the context of the HOR study area and the barrier treatment, barrier status (Off/On), or no barrier, present for that time period.

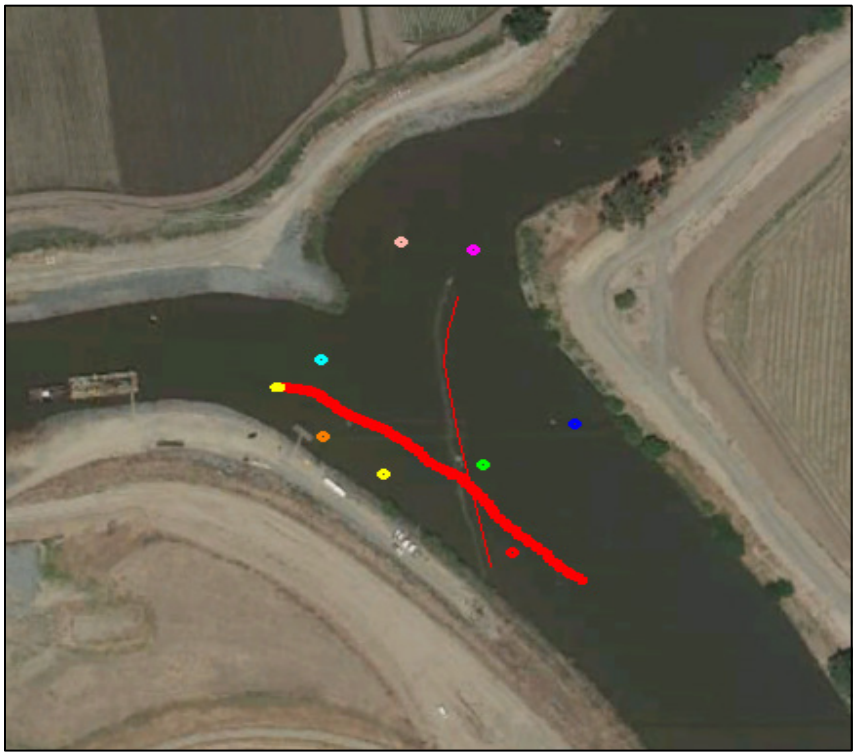
Each tagged fish track was evaluated to determine if the tagged fish encountered the barrier (if present), if the tagged fish was deterred by the barrier (if BAFF was present and status was On), if the tagged fish exhibited predator-like behavior, and finally the ultimate fate of the tagged fish.

The guidelines for categorizing each tagged fish track into deterred (BAFF years 2009 and 2010), non-deterred (BAFF years 2009 and 2010), predation, route selected (San Joaquin River or Old River), or unknown, are listed in Appendix E. There were small differences in the guidelines for each study year based on the presence of a BAFF, the presence of a physical rock barrier (which caused large scale hydraulic effects unlike a non-physical barrier), or the absence of any barrier. Example tracks for tagged fish that were categorized as deterred, non-deterred, and predation are shown in Figures 5-10, 5-11, and 5-12, respectively. More examples of tracks for each deterrence category for each year are presented in Appendix E.



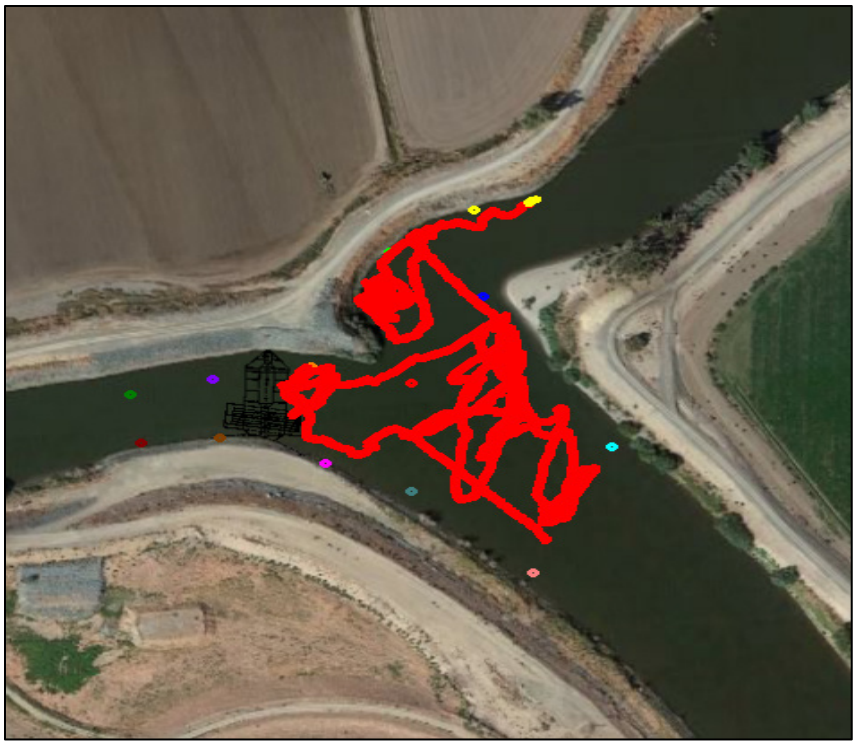
Source: Hydroacoustic Technology, Inc. 2013

Figure 5-10 **Tagged Chinook Number 5674.21 Deterred by the BAFF (On) at 03:38 PDT on May 15, 2009 and Exiting the Array down the San Joaquin River**



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-11 **Tagged Chinook Number 5437.14 Passing through the BAFF (On) at 0:27 PDT on April 28, 2010 and Exiting the Array down the Old River**



Source: Hydroacoustic Technology, Inc. 2013

Figure 5-12 **Tagged Chinook Number 2203.03 (designated as having been eaten by a predator) Showing Directed Movement Downstream at the Beginning of the Track, then Becoming "Predator-Like," Exhibiting Both Upstream and Looping Movement between 19:16 and 21:24 PDT on May 20, 2012 at the HOR Study Area**

Tag Drags and Ping-Arounds

In each year, after the hydrophones were set up, several tag drags were conducted. The tag drags ensured that a tag could be heard by three or more hydrophones at all locations within the hydrophone array.

The tagged fish-release periods are defined in Table 5-4. During the periods when the tagged fish were in the water, ping-arounds were done periodically using AcousticTag software. The ping-around information was used to improve the precision of the tag positions. These tag positions were used to build the 2D tracks. Tag positioning precision was estimated by HTI personnel at ≤1 m (Johnston, pers. comm., 2009).

5.2 EVALUATION OF JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

5.2.1 GROUPING JUVENILE SALMONIDS INTO SAMPLES

The data analyses described were reanalyses of the data published in Bowen et al. (2012) and Bowen and Bark (2012), combined with analyses of new data collected in 2011 and 2012. An essential element of this reanalysis was assigning tags to samples depending on the time they were at the HOR study area, rather than the date and time at which they were released.

The first sample was assigned when the first fish arrived at the HOR study area. As long as the barrier state did not change, ambient light did not cross a critical threshold, and average water velocity did not cross a critical threshold, each fish that arrived was placed in this sample. When barrier state, or light, or velocity changed, a new sample was assigned. In this manner, all tagged fish were placed in samples. Samples with only one fish were removed from the analysis.

Barrier state was defined by the type and its status. For example, in 2009 and 2010, the barrier was a BAFF and the status was determined by whether the BAFF was turned on or off. In 2011, no barrier was installed. Thus, this treatment was referred to as "No Barrier" and the barrier status was always off. In 2012, a physical rock barrier was installed, thus the barrier was always on.

The critical threshold used for determining low- and high-light conditions was 5.4 lux. This critical threshold was chosen with regard to the operation of the BAFF. Based on the work of Anderson et al. (1988) on juvenile Chinook salmon strobe-light avoidance reactions, it was assumed that if the ambient light was ≥ 5.4 lux, then ambient light may influence the ability of the high-intensity modulated lights to produce a reaction in juvenile Chinook salmon encountering the BAFF. This critical light threshold (5.4 lux) was also used in analysis of the effects of a non-physical barrier at Georgiana Slough (DWR 2012).

The critical velocity threshold used to determine low- and high-velocity conditions was 0.61 m/s average channel velocity. This critical velocity threshold was selected based on a conservative estimate of the sustained swimming speed of juvenile Chinook salmon of 4.37 body lengths per second (BL/s) (Appendix B: Table B-1). This threshold was designed to protect juvenile Chinook salmon measuring 57 mm FL, which was the minimum size observed for a fall-run individual at the Tracy Fish Collection Facility and Skinner Delta Fish Protective Facility from August 1, 2011, through July 31, 2012 (NMFS 2013). Therefore, at a sustained swimming speed of 4.37 BL/s, a 57-mm FL juvenile Chinook salmon could swim 0.25 m/s. Thus, it was assumed that a fall-run juvenile had the capacity to swim away from the BAFF when the approach velocity was ≤ 0.25 m/s. An approach velocity of 0.25 m/s occurred when the average channel velocity was 0.61 m/s for the angle incident to the flow for the 2009 BAFF (24°) (Figure 5-1).

5.2.2 CALCULATION OF OVERALL EFFICIENCY

Overall efficiency (O_E) for the BAFF and the rock barrier were determined for each sample using Equation 5-1, in relation to start and finish lines similar to those depicted in Figure 5-13 (exact locations differed depending on hydrophone coverage in each year).

Equation 5-1:

$$O_E = S_A/L_A$$

Where:

O_E = overall efficiency,
S_A = the number of tags that left the HOR study area downstream via the San Joaquin River, passing the San Joaquin River finish line, and
L_A = the number of tags that entered the HOR study area from the upstream San Joaquin River, passing the San Joaquin River start line.



Source: Data compiled by AECOM in 2013

Figure 5-13

Head of Old River Study Area: Start and Finish Lines and 2012 VEMCO Hydrophone Placements

The calculation of O_E for 2011 (the "No Barrier" year) was the same mathematically as the calculation of O_E in Equation 5-1; therefore, it was possible to compare this parameter statistically across years. The hypotheses used for these comparisons are discussed under "Primary Objectives and Hypotheses Related to Juvenile Salmonid Routing, Including Barrier Effects" in Section 1.2.2, "Juvenile Salmonid Routing Including Barrier Effects," in Chapter 1.

5.2.3 CALCULATION OF PROTECTION EFFICIENCY

Protection efficiency (P_E) for the BAFF and the rock barrier were determined for each sample using Equation 5-2, in relation to start and finish lines similar to those depicted in Figure 5-13 (exact locations differed depending on hydrophone coverage in each year).

Equation 5-2:

$$P_E = S_N/(S_N+L_N)$$

Where:

P_E = protection efficiency,
S_N = the number of juvenile salmonids that left the HOR study area via the downstream San Joaquin River, passing the San Joaquin River finish line that were not eaten, and
L_N = the number of juvenile salmonids that left the HOR study area via Old River, passing the Old River finish line that were not eaten.

This calculation for P_E in relation to the BAFF and rock barriers (Equation 5-2) was also used to calculate P_E for 2011 (the "No Barrier" year), noting that there was no actual "protection" afforded by the lack of a barrier. Because the same equation was used for all years, it was possible to compare these two parameters statistically across years. The hypotheses used for these comparisons are discussed under "Primary Objectives and Hypotheses Related to Juvenile Salmonid Routing Including Barrier Effects" in Section 1.2.2, "Juvenile Salmonid Routing Including Barrier Effects," in Chapter 1.

5.2.4 CALCULATION OF BARRIER DETERRENCE EFFICIENCY

Deterrence efficiency (D_E) for the BAFF when it was on and off was evaluated using 2009 and 2010 data. A juvenile salmonid was determined to have experienced the BAFF if it came within 10 m of the BAFF in low-light conditions and if it came within 3 m of the BAFF in high-light conditions. D_E was determined for each sample according to Equation 5-3.

Equation 5-3:

$$D_E = R/E$$

Where:

D_E = barrier deterrence efficiency,
R = the number of tags that were deterred, and
E = the number of tags that experienced the BAFF.

D_E was calculated only for the years in which the BAFF was used: 2009 and 2010. The hypotheses used for these comparisons are discussed under "Primary Objectives and Hypotheses Related to Juvenile Salmonid Routing Including Barrier Effects," in Section 1.2.2, "Juvenile Salmonid Routing Including Barrier Effects," of Chapter 1.

5.2.5 CALCULATION OF BAFF EFFECT

It was possible to calculate the BAFF's effect when two samples occurred immediately adjacent in time, and therefore had the same light and velocity conditions, but where the BAFF was changed as part of an tagged manipulation. Thus, there was a directly comparable BAFF "on" to "off" condition. The BAFF effect was calculated according to a simple calculation (Equation 5-4).

Equation 5-4:

$$F = E_N - E_O$$

Where:

F = BAFF effect,
E_N = efficiency with the BAFF on, and
E_O = efficiency with the BAFF off.

The results for BAFF effect are reported in Chapter 6, "Results." The results are uncommon because it was unusual for the conditions to occur to acquire a BAFF effect sample.

5.2.6 STATISTICAL COMPARISONS

Using the samples assigned as described in Section 5.2.1, each of the null hypotheses described in Section 1.2, "Study Design, Objectives, and Hypotheses," was tested statistically. Additionally, when appropriate, the null hypotheses were also tested at each combination of light and velocity.

Four dependent variables of interest were compared. The first dependent variable was O_E, which provided an estimate of the proportion of tags that left the HOR study area via the San Joaquin River. The second dependent variable was P_E, which provided an estimate of the proportion of juvenile salmonids that left the HOR study area via the San Joaquin River that were not eaten. The third variable of interest was D_E, which provided an estimate of the proportion of juvenile salmonids that turned away from or were guided by the BAFF. The fourth variable of interest was BAFF effect, calculated when possible, which was the difference in an efficiency metric (O_E, P_E, or D_E) between the BAFF on and off.

An independent variable of interest was BAFF status, specific to the years when the BAFF was operated. In 2009 and 2010, it was possible to obtain a set of samples with the BAFF on and off for comparison. The comparison between BAFF on and off showed whether or not operation of the BAFF deterred juvenile Chinook salmon from entering Old River. If BAFF operation could not be shown to be better with the BAFF on compared to off, then the BAFF would have no utility as a fish deterrent.

The independent variable of primary interest was treatment, which had four states: (1) BAFF-2009; (2) BAFF-2010; (3) No Barrier-2011; and (4) Rock Barrier-2012. Each of these treatments occurred in a particular year

because it was not logistically feasible to change the barriers during a single study season. Thus, each treatment was also a function of a particular combination of physical attributes described in Chapter 3, "Physical Parameters." Because the physical attributes might have significant impact on barrier function, the treatment/year was depicted as the independent variable.

The independent variables of secondary interest were light intensity and water velocity. These were developed because of published literature accounts (Perry et al. 2012; Welton et al. 2002) of their effects on the operation of a BAFF. Thus, when appropriate, O_E, P_E, and D_E were evaluated at two light and velocity levels. The critical light and velocity thresholds are described in Section 5.2.1.

For each comparison, a one-way analysis of variance (ANOVA) was conducted for an independent variable and a dependent variable. For example, the first comparison was made in 2009: O_E was evaluated for the BAFF on versus off. Then, after the ANOVA was completed, the data were evaluated to determine whether they met the assumptions of the ANOVA procedure (Sokal and Rohlf 1995). With only one exception in the entire study, the data did not meet the assumptions of the ANOVA, and it was necessary to rely on a nonparametric equivalent: the Kruskal-Wallis Test (Hollander and Wolfe 1973).

The test statistic and P-value were reported. If the null hypothesis was rejected and there were more than two sets of samples, the sets of samples were then subjected to pair-wise comparisons to determine which populations were different. When more than one two-sample comparison was made, a Bonferroni adjustment in the critical alpha was made to control the experiment-wise error rate (Sokal and Rohlf 1995).

5.3 EVALUATION OF PREDATION ON JUVENILE SALMONIDS INCLUDING BARRIER EFFECTS

5.3.1 PROPORTION EATEN (UNIVARIATE ANALYSES)

The proportion of tagged fish in a sample that were eaten was determined for each sample according to Equation 5-5.

Equation 5-5:

$$C = C_P/L_A$$

Where:

C = sample proportion eaten;
C_P = the number of tags that were identified as having been eaten; and
L_A = the number of tags that entered the HOR study area from the upstream San Joaquin River, passing the San Joaquin River start line.

The procedure for grouping juvenile salmonids into samples is described in Section 5.2.1, "Grouping Juvenile Salmonids into Samples." The sample proportion eaten was used for testing hypotheses $H8_0$, $H9_0$, and $H10_0$, which were described under "Objectives and Hypotheses Related to Proportion Eaten" in Section 1.2.3, "Predation on Juvenile Salmonids, Including Barrier Effects." The sample proportion eaten is reported with the results of the statistical comparisons used for the hypothesis testing. In addition, when mean sample proportion

eaten was reported, population proportion eaten was also reported. The population proportion eaten for a given year is the grand proportion eaten determined by the total number of tagged juveniles eaten divided by the total number of tagged juveniles passing by the HOR study area in that year. The population proportion eaten summarizes the proportion eaten across all barrier states and light and velocity levels, and is comparable to the probability of predation described in Section 5.3.2, "Probability of Predation (Generalized Linear Modeling)," and in San Joaquin River Group Authority reports (SJRGA 2010, 2011, and 2013).

Statistical comparisons to test hypotheses $H8_0$, $H9_0$, and $H10_0$ were made with univariate tests in an analogous manner to that described for O_E, P_E, and D_E in Section 5.2.6, "Statistical Comparisons." In addition, interpretation was conducted in the same way using a comparison of the P-value and critical alpha (0.05), to determine if the null hypothesis should be rejected.

5.3.2 PROBABILITY OF PREDATION (GENERALIZED LINEAR MODELING)

The probability of tagged juvenile salmonids being preyed upon at the HOR study area was assessed in relation to several predictor variables that were hypothesized *a priori* to have potential influence on predation (see "Objectives and Hypotheses Related to Proportion Eaten" in Section 1.2.3, "Predation on Juvenile Salmonids Including Barrier Effects)": discharge, water temperature, turbidity, light level, juvenile size, small-fish density, and large-fish density. Discharge is highly correlated with velocity, and thus chosen for inclusion in modeling, as it is the more commonly used variable for planning and operations purposes. Discharge has been positively associated with salmonid survival probability through the Delta in several studies (Cavallo et al. 2013; Newman 2003; Perry 2010; but see also Zeug and Cavallo 2013). This may be because greater discharge results in shorter travel time or more direct migration routing, and therefore, less exposure to predators (Anderson et al. 2005). It was hypothesized that this predictor would be negatively related to predation probability at the HOR study area. Salmonid survival in the Delta has been demonstrated to be negatively associated with water temperature (Newman 2003; Zeug and Cavallo 2013), perhaps because predatory fish energy requirements increase at higher temperatures, and so food requirements are greater (Hanson et al. 1997). It was hypothesized that water temperature would be positively related to predation probability at the HOR study area.

Studies have found a positive relationship between turbidity and survival of Delta native fishes, both in the field (Chinook salmon: Newman 2003) and in the laboratory (delta smelt: Ferrari et al. 2013), presumably because the visual range of predators is less under more turbid conditions (Aksnes and Giske 1993). Similarly, light level affects the visual range of predators (Aksnes and Giske 1993), and some predatory species, such as largemouth bass, predominantly feed during the day (Moyle 2002). Accordingly, it was hypothesized that predation probability in the HOR study area would be negatively related to turbidity and positively related to light level.

The size of juvenile Chinook salmon migrating through the Delta was found to be positively associated with subsequent ocean recovery rate by Zeug and Cavallo (2013), possibly because of greater escape ability and reduced probability of being eaten by gape-limited predators. Predation probability at the HOR study area, therefore, was hypothesized to be negatively related to juvenile size. Small-fish density at the HOR study area (see predictor definition and description that follows; Table 5-5) was hypothesized to be negatively related to predation probability, reflecting the potential that greater density of alternative prey would reduce the predation risk to any individual juvenile. Large-fish density at the HOR study area was hypothesized to be positively related to predation probability because there is evidence that predator abundance is negatively related to juvenile Chinook salmon survival in the Delta (Cavallo et al. 2013). Barrier status also was included as a predictor (see

further discussion that follows), with the null hypothesis that there was no difference between barrier states in predation probability at the HOR study area. Survival in relation to barrier status at the HOR study area previously had been evaluated at a broader scale. For example, recent analysis by Zeug and Cavallo (2013) found no well-supported effect on ocean recovery rate of Chinook salmon in relation to installation of the physical rock barrier during the juvenile migration period through the Delta, whereas previous analysis by Newman (2008) suggested that survival was higher in the San Joaquin River than in Old River, and therefore, effective installation of the rock barrier would increase survival through the Delta.

Table 5-5
Summary of Predictor Variables Used in Generalized Linear Modeling of Juvenile Salmonid Probability of Predation at the Head of Old River Study Area

Variable (Unit)	Location	Source	Transformation	Notes
Water temperature (°C)	SJL	CDEC (Baldwin, pers. comm., 2013)	None	15-minute average data
Discharge (m^3/s)	SJL	CDEC (Baldwin, pers. comm., 2013)	None	15-minute average data
Turbidity (NTU)	MSD	CDEC (Dempsey, pers. comm., 2013)	None	15-minute average data
Ambient light (lux)	Manteca (CIMIS site #70)	CIMIS (State of California 2009)	Natural logarithm + 1	Original CIMIS data (Langley/day) were first converted into PAR per Clark et al. (2009: PAR, $\mu mol/m^2/s$ = 1.1076*Langley/day), and subsequently PAR was converted into lux per Apogee Instruments, Inc. (2013:Lux = 54*PAR). Original hourly data were linearly interpolated to 15-minute increments for consistency with water quality data.
Small fish density (<15 cm FL/10,000 m^3)	Mossdale (trawling)	USFWS survey data (Speegle, pers. comm., 2011 and 2013)	Natural logarithm + 1	
Large fish density (> 30 cm TL/10,000 m^3)	HOR study area	Mobile hydroacoustic data (this study)	Natural logarithm + 1	

Notes: °C = degrees Celsius; CDEC = California Data Exchange Center; CIMIS = California Irrigation Management Information System; cm = centimeters; m^3 = cubic meters; m^3/s = cubic meters per second; MSD = San Joaquin River at Mossdale; NTU = nephelometric turbidity units; PAR = photosynthetically active radiation; SJL = San Joaquin River at Lathrop; USFWS = U.S. Fish and Wildlife Service
Source: Present study

Each tagged juvenile entering the HOR study area was assigned a fate according to Bowen et al. (2012) and Bowen and Bark (2012) (i.e., visual examination of juvenile tracks using Eonfusion software (Myriax Software, Hobart, Tasmania, Australia); see Appendix E, "Fish Fate Determination Guidelines"). Tracks that initially entered the HOR study area with well-directed downstream movement but subsequently displayed evidence of predation (e.g., looping movements through the study area without clear downstream movement) were assigned the fate of "predation." It was not possible to assign a fate to every fish that entered the HOR study area, because it was not always clear when fish may have been preyed upon or may have survived; only fish that were

successfully classified as preyed upon or survived were included in the analysis. Complex hydrodynamics within the HOR study area caused by the physical rock barrier during 2012 made fate assignment particularly challenging for data from this year, and hydrodynamic modeling (see Section 3.2, "Velocity Field") was used to aid these classifications. The qualitative procedure used to assign fates is being compared to quantitative mixture model analyses for data generated at Georgiana Slough in 2012 (DWR in review; Romine et al. 2014).

The predictor variables included in the predation-probability analyses generally were the same as those used for analyses of greater than 30-cm fish abundance from mobile hydroacoustics (Table 5-5) (see also "Statistical Methods" in Section 5.4.2, "Hydroacoustic Surveys"). Abiotic variables (discharge, water temperature, turbidity, and ambient light) were based on the closest 15-minute observation to the time that the juveniles were at their minimum distance from common reference points: the 2009 or 2010 non-physical barrier alignments. Two estimates of the density of large fish (> 30 cm TL), taken to be indicators of potential predatory fish abundance at the HOR study area, were included in the analysis based on side-looking and down-looking mobile surveys conducted in 2011 and 2012 (see Section 5.4.2, "Hydroacoustic Surveys"). Consistent with small-fish density estimates, the large-fish density estimates associated with each juvenile's fate were averaged over the 3-day period, ending the day a juvenile entered the HOR study area. A 3-day period was used to increase the number of juveniles that could be retained in the analysis by avoiding missing values for this predictor variable. In addition, juvenile length was included per the hypothesis that larger fish may have a greater probability of survival.

Three analyses of predation probability were conducted based on species, barrier/discharge conditions, and the availability of > 30-cm fish density data from mobile hydroacoustic surveys. The first analysis tested hypothesis H11 (see Table 1-2 in Section 1.2.3, "Predation on Juvenile Salmonids Including Barrier Effects") and was based on tagged juvenile Chinook salmon predation data from 2009, 2010, and 2012 (n = 1,169); it included all previously mentioned predictor variables except large fish density from mobile hydroacoustics, which was not undertaken in 2009 and 2010. Barrier status was included as a predictor variable with three levels: BAFF on, BAFF off, and physical rock barrier. Data from 2011 were not included in this analysis because it would have been difficult to ascertain whether any differences in predation probability resulted from the absence of the barrier or from the very high discharge; these variables were confounded. The second analysis tested hypothesis H12 and was based on Chinook salmon predation data from 2011 and 2012 (n = 876); it included all predictor variables except barrier status. The third analysis tested hypothesis H13 and was based on steelhead predation data from 2011 (n = 163); it included all predictor variables except barrier status. There were insufficient data (n = 5) from 2012 for inclusion in the steelhead predation probability analysis.

The probability-of-predation analyses were undertaken using a GLM within a model averaging/information theoretic framework (Burnham and Anderson 2002) based on the R software (Version 3.0.0; R Core Team 2013) package "glmulti" (Calcagno and de Mazancourt 2010). This modeling technique has been applied on a number of recent occasions for fish research in the San Francisco Bay–Delta and Central Valley (e.g., Beakes et al. 2012; Perry et al. 2012; Zeug and Cavallo 2013). In addition to the standard reference text (Burnham and Anderson 2002) for this modeling technique, a useful summary is provided by Mazerolle (2006).

The glmulti package was used to provide all possible first-order GLMs for probability of predation (response = 1) versus survival (response = 0), with the response modeled with a binomial distribution and logit link function. The relative level of support for each possible model was estimated in glmulti with Akaike's Information Criterion (AIC), corrected for small sample sizes (AIC_c) (Mazerolle 2006). The difference in AIC_c, Δ_i, between each model

and the best model (i.e., the model with the lowest AIC_c) was calculated, and Akaike weights (w_i) were calculated based on the Δ_i. Model averaging of the predictor variable coefficients was undertaken based on the Akaike weights for each model, and unconditional confidence intervals were calculated for each coefficient (Mazarolle 2006). The importance of each predictor variable was assessed by summing the w_i of all models in which the variable appeared; following Calcagno and de Mazancourt (2010), importance of 0.8 or greater was used to infer support for a variable's potential influence on predation probability, in addition to unconditional 95% confidence intervals for variable coefficients not overlapping zero (per Zeug and Cavallo 2013).

GLMs including predictors were assessed to provide a better fit to the data than intercept-only models if the AIC_c of the full model (with all predictors included) was three or more units greater than the AIC_c of the intercept-only model (Zeug and Cavallo 2013). Model fit to observed data was assessed using similar methods to those of Beakes et al. (2012) and Perry et al. (2012). Model-fit assessment was conducted with the PresenceAbsence package of the R software (Freeman and Moisen 2008). As described by Beakes et al. (2012), an optimized threshold based on Kappa was calculated for each GLM. The threshold value was set where Kappa was maximized for each GLM, and this threshold value was used to estimate Kappa and several additional threshold-dependent model performance statistics: Cohen's Kappa statistic, percent correctly classified (PCC), sensitivity, and specificity. Each statistic is a measure of the capacity to accurately discriminate the correct outcome of predation of tagged juvenile salmonids observed in the data, where probabilities that exceed the threshold were classified as predation (positive) and probabilities below the threshold were classified as survival (negative). Beakes et al. (2012) described these statistics as follows:

> The Kappa statistic is a measure of all possible outcomes of presence or absence that are predicted correctly, after accounting for chance predictions; it is generally accepted as a conservative and standardized metric for comparing the predictive accuracy of binary models regardless of their statistical algorithm (Manel et al. 2001). PCC compares the proportion of outcomes correctly classified. In this application, sensitivity represents the proportion of true positives correctly identified, and specificity is the proportion of true negatives correctly identified, where 1-specificity is the proportion of false positives.

In addition to the threshold-dependent model performance statistics, a threshold-independent measure of model performance was also used: the area under the receiver operating characteristic (ROC). This measure indicates the probability of detecting a true signal (sensitivity) versus a false signal (1–specificity) (Hosmer and Lemeshow 2000). The area under the ROC is interpreted based on the following general rule (Hosmer and Lemeshow 2000: 162):

- If ROC = 0.5, this suggests no discrimination (i.e., the net result is the same).
- If 0.7 ≤ ROC less than 0.8, this is considered acceptable discrimination.
- If 0.8 ≤ ROC less than 0.9, this is considered excellent discrimination.
- If ROC ≥ 0.9, this is considered outstanding discrimination.

Similar to Perry et al. (2012), the fit of the GLM of juvenile Chinook salmon predation in 2009/2010/2012 was assessed by plotting the observed response in relation to model predictions. This involved plotting predation proportions in light (≥ 5.4 lux) and dark (< 5.4 lux) conditions across all three levels of the barrier status predictor (non-physical barrier on, non-physical barrier off, and physical rock barrier) versus the predicted predation probabilities, using the average continuous covariate values for each of these levels.

5.4 EVALUATION OF BEHAVIOR AND DENSITY CHANGES IN PREDATORY FISHES

5.4.1 PREDATORY FISH ACOUSTIC TAGGING

FIELD METHODS

Predatory fish (striped bass, largemouth bass, channel catfish, and white catfish) at the HOR study area were captured by hook-and-line fishing using bait and artificial lures, primarily in 2011 and 2012. Three additional fish were captured and tagged in 2009 and 2010; two fish (both striped bass) tagged outside the study area that moved into the HOR study area were also included in the analysis. Barbed circle hooks were used during bait fishing to minimize hooking injuries. Captured predatory fish having hooking or other injuries and/or displaying obvious abnormal behavior were released immediately and not included in the study. Predatory fish capture occurred primarily from fishing boats, but also from shoreline locations such as the sandy point on the right bank of the San Joaquin River across from the divergence with Old River. Hooks were removed carefully immediately after capture, and fish were placed in aerated live wells (1,500 gallons per hour pumping capacity) filled with water of temperature nearly identical to river temperature. To increase tagging efficiency, tagging generally was undertaken after several fish had been captured (holding duration generally was no more than 1 to 2 hours, and sometimes less than 1 hour). Tagging took place either on board the fishing boat or on the sandy point mentioned previously.

Predatory fish retained for tagging were identified to species and had length (FL in 2011, TL in 2012) and weight (2012) recorded. Tagged predatory fish generally were 30 cm or longer to allow a focus on the individuals most likely to prey on primarily juvenile Chinook salmon. Predatory fish typically consume prey that is 20% to 30% of their length (Uphoff 2003), and thus, would have greater potential to consume juvenile Chinook salmon of approximately 80 to 100 mm when 30 cm or larger. It is acknowledged that predatory fish occur at smaller sizes than 30 cm. Fish were fitted with HTI 795*LX* or 795*LG* tags (see Table 5-2) that were attached externally in the same manner described by Vogel (2011). External tag attachment consisted of two plastic-coated stainless steel wires attached to the transmitter, inserted through the musculature under the dorsal fin using hypodermic needles, and held in place with two plastic plates crimped on the opposite side of the fish.

Each tag had a unique four-digit identifier that was used to cross-reference detections with the identity and characteristics of tagged fish as recorded in field datasheets. The life span of the tags used in this study is several hundred days, depending on pulse width and pulse rate interval.

Fish generally were released where they were tagged. In 2011, fish releases typically occurred near capture locations. In 2012, fish were released near capture locations (which included the San Joaquin River upstream of the HOR study area and Old River downstream of the HOR study area, to allow an examination of how predatory fish behaved in relation to each of the barriers), from the sandy point referenced previously, or from other locations chosen to ensure that the fish remained within the range of the acoustic array. Fish tagging lasted from May 6 through June 15 in 2011 and from April 22 through May 24 in 2012.

DATA ANALYSIS

A total of 102 predatory fish were captured and tagged (including two individuals captured and tagged elsewhere in the south Delta), but only 84 were detected within the acoustic array at the HOR study area and were included in this analysis. The acoustic tags used for predatory fish in this study emitted double pulses every few seconds. Only the first of the double pulses was used in the present analysis.

Residence Time

Residence time at the HOR study area is an important factor because it has implications for the feasibility of predatory fish control (Gingras and McGee 1997). The length of time that each tagged predatory fish spent at the HOR study area was estimated based on detections by the HTI array and summarized as the number of days detected. Examination of the data indicated that several fish were not detected continuously for long periods, but were frequently detected over many days, suggesting that they occupied areas on the periphery of the array's detection ability. In addition, the potential length of time that each tagged fish could spend at the HOR study area depended on when each fish was tagged relative to the deactivation and removal of the acoustic array at the end of the study period. Deactivation/removal dates were May 20, 2009, May 25, 2010, June 22, 2011, and May 31, 2012.

To account for these factors, the percentage of possible dates that a tagged predator spent at the HOR study area between tagging/release and array deactivation/removal was calculated. For example, largemouth bass tag code 3324 was captured, tagged, and released on May 24, 2011, and subsequently detected from June 9 through 11, June 13, June 15 through June 18, and June 20 through June 22, 2011, for a total of 11 dates detected out of 29 dates between the day of tagging and the day of array deactivation/removal (i.e., 38%). Data calculated in this manner for all individual fish were then summarized for several groups defined by species, year, and—for 2012 data only—location of release (referred to as "San Joaquin River" for fish released upstream of the physical rock barrier and "Old River" for fish released downstream of the rock barrier).

Few fish (one largemouth bass and four striped bass, including two individuals captured outside the HOR study area) were tagged in 2009 and 2010. The striped bass were grouped together for analysis because BAFF was installed in both years. A resampling method ("bootstrapping") (Brown et al. 2012) was used to produce statistical summaries of the data to account for the small sample sizes (i.e., relatively few [generally less than 10] fish in each species/year/release location group). For each species/year/release location group, the percentage-of-dates-detected data for fish within the group were resampled with replacement until each resample contained the same number of observations (fish) as the original sample. This procedure was repeated 10,000 times, and the arithmetic mean was calculated for each of the 10,000 resamples. The 10,000 resamples were then used to generate statistical summaries for the percentage of dates detected within each species/year/release location group. The quantities estimated included the mean (50th percentile of the 10,000 resamples), interquartile range (25th and 75th percentiles of the 10,000 resamples), and 95% confidence interval (2.5th and 97.5th percentiles of the 10,000 resamples).

Spatial Analysis

A GIS map of the HOR study area was divided into zones to facilitate spatial analysis (Figure 5-14). A total of 83 zones were delineated on the basis of bathymetric features such as the scour hole, proximity to shoreline, and the locations of the 2012 rock barrier and the 2009/2010 BAFF alignments. Three major groupings of zones encompassed the San Joaquin River upstream of the divergence with Old River (zones 1–33), San Joaquin River downstream of the divergence with the Old River (zones 34–59), and the HOR (zones 60–83). Within each of these major zonal groupings, nearshore ("buffer") zones were within 5 m of shore, and offshore zones were greater than 5 m from shore. The scour hole in the San Joaquin River downstream of the Old River divergence was divided longitudinally (upstream/downstream) approximately in two, and several depth zones were defined on the basis of four major elevation ranges from 2012 bathymetric data:

- -12 to -17 feet [-3.66 to -5.18 m] NAVD of 1988 (zones 44, 45, 52, and 59)
- -17 to -27 feet [-5.18 to -8.23 m] (zones 46, 47, 53, 58)
- -27 to -32 feet [-8.23 to -9.75 m] (zones 48, 49, 54, and 57)
- deeper than -32 feet [-9.75 m] (zones 50, 51, 55, 56)

The 2012 rock barrier was represented by several zones encompassing the base of the barrier (zones 70–73) and the culverts (zones 67 and 75), in addition to near-field areas within 5 m of the barrier and its culverts (zones 65, 66, 68, and 69 upstream; zones 74, 76, 77, and 78 downstream). The extent of the barrier base that was accessible by fish in 2012 was variable based on water level; the trapezoidal shape of the barrier (relatively narrow top tapering to a wider base) is evident in the aerial image underlying Figure 5-14 (the top of the barrier is the white area in zones 70–73). The immediate (within 5 m) vicinity of the BAFFs was delineated for the 2009 (zones 27–33) and 2010 (zones 20–26) alignments.

Geo-referenced datasets (easting and northings, UTM Zone 10 N) of confirmed positive detections (i.e., "positive echoes") were output for each tagged predatory fish. To facilitate manipulation of the very large datasets generated during the study for spatial analysis, eastings and northings were rounded to the nearest meter for each detection. A grid of 1-m by 1-m points was generated that included the area of the HOR study area spatial zones (Figure 5-14), so that each grid point was assigned to a single spatial zone. Each predatory fish detection was merged with the database of grid points and spatial zones. The number and percentage of detections occurring within each spatial zone was calculated for each predatory fish. Similar to the analysis of residence time (described previously), the percentage of detections was summarized statistically for each species/year/release location group using 10,000 resamples of grouped spatial zones. Only predatory fish with at least 1,000 detections were included in the analysis to exclude information on fish that rapidly left the study area. The threshold of 1,000 detections was chosen on the basis of this value generally representing at least several hours of continuous detections, as opposed to rapid exit from the study area. In addition, only species, year, and release location groups with at least three tagged fish were included in the analysis.[1] A total of 14 spatial zone groupings were used for the analysis:

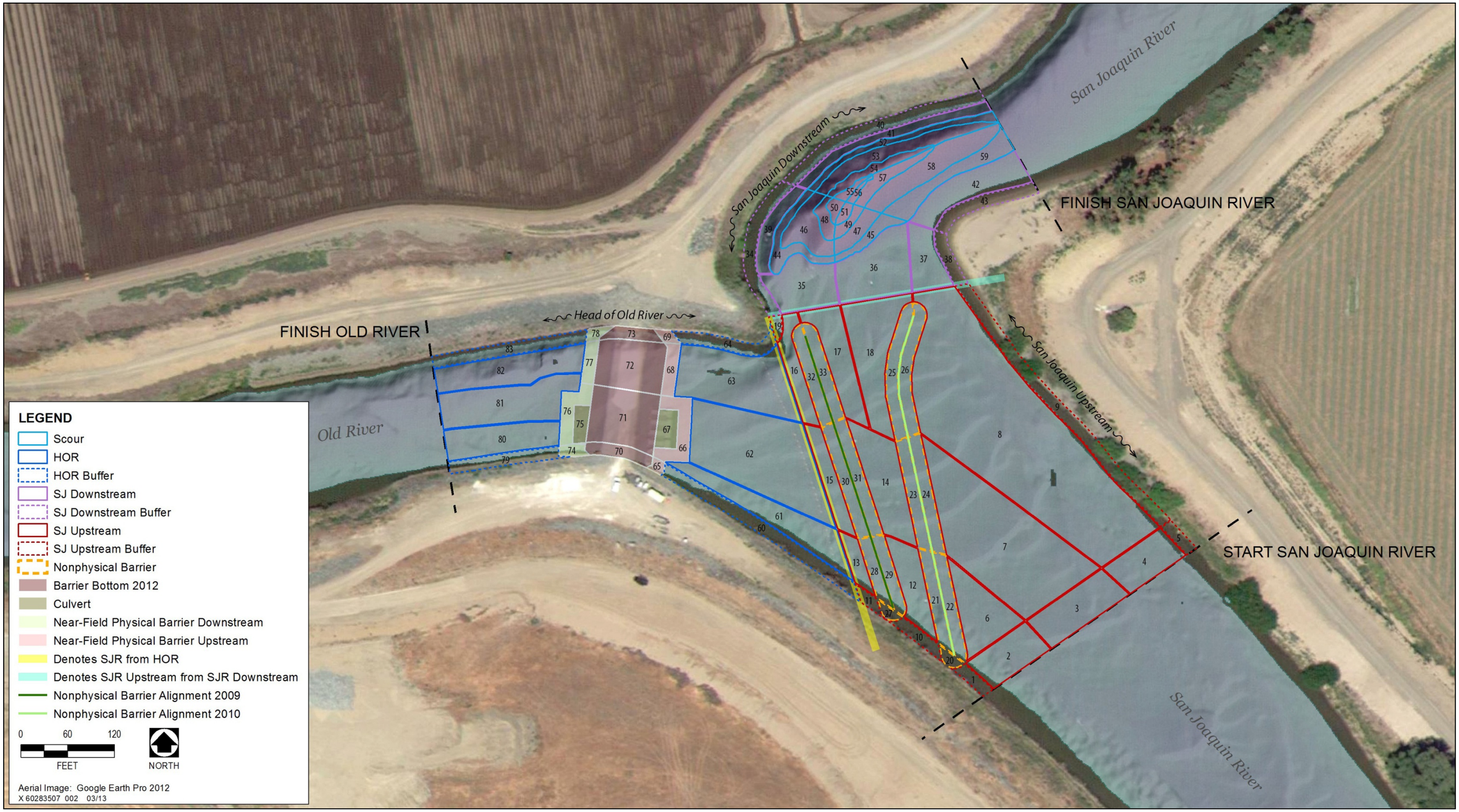
- San Joaquin River upstream of the Old River divergence, offshore (zones 2–4, 6–8, 12–18)
- San Joaquin River upstream of the Old River divergence, nearshore (zones 1, 5, 9–11, 19)

[1] Two striped bass (tag codes 2024 and 2472) that were tagged and released in 2010 met the criterion of 1,000 detections, but no other striped bass met this criterion in 2010. The results of these fish are discussed separately because their association with the 2010 BAFF is of management interest. For the same reason, the results for largemouth bass tag code 4306 are discussed in relation to the 2009 BAFF.

- Less than 5 m from the 2010 non-physical barrier (zones 20–26)
- Less than 5 m from the 2009 non-physical barrier (zones 27–33)
- San Joaquin River downstream of the Old River divergence, offshore (zones 35–37, 39, 41–42)
- San Joaquin River downstream of the Old River divergence, nearshore (zones 34, 38, 40, 43)
- Scour hole (zones 44–59)
- Head of Old River upstream of the 2012 rock barrier, offshore (zones 61–63)
- Head of Old River upstream of the 2012 rock barrier, nearshore (zones 60, 64)
- Near-field (less than 5 m) upstream of the 2012 rock barrier (zones 65–69)
- 2012 rock barrier (zones 70–73)
- Near-field (less than 5 m) downstream of the 2012 rock barrier (zones 74–78)
- Head of Old River downstream of the 2012 rock barrier, offshore (zones 80–82)
- Head of Old River downstream of the 2012 rock barrier, nearshore (zones 79, 83)

The spatial zones differ in size, and therefore, also differ in the number of 1-m by 1-m grid points that they possessed. To provide an indication of the extent of use of each zone relative to its size, a simple index was calculated for each group of spatial zones: percentage of detections within the grouped zone divided by percentage of grid points within the grouped zone. Values greater than 1 for this index indicated that the zone was used more frequently than would be expected based on its relative size. Predatory fish tagged in 2012 were released into either Old River downstream of the 2012 rock barrier or the San Joaquin River upstream of the 2012 rock barrier; therefore, the number of grid points used as the denominator in the calculation was adjusted to exclude the zones to which the fish would not have had access. This included the apparently unwetted portions of the 2012 rock barrier (i.e., zones 70–73 in Figure 5-14) that formed the bottom of the barrier. This adjustment removed approximately 79% of the area of zones 70–73 from consideration for fish released into the Old River downstream of the rock barrier in 2012, and approximately 71% of the area of zones 70–73 for fish released upstream of the rock barrier in 2012. In addition, the 2011 acoustic array was not able to detect fish beyond the zones downstream of the 2012 rock barrier bottom, so these zones were excluded from the calculations for fish released in 2011.

Near-surface water velocity within the areas occupied by tagged predatory fish in 2012 was estimated using velocity fields estimated from data collected with the SL-ADCP (see Section 3.2, “Velocity Field”). Tag detection data for each tagged predatory fish released upstream of the 2012 rock barrier that had more than 1,000 detections was merged with the 15-minute estimated velocity data. This was done by assigning each tag detection to the nearest 5-m by 5-m velocity grid point for the same 15-minute period in which the tag detection had occurred. Only tag detections within the grid of velocity estimates were included. The velocities at which each tagged fish had occurred were compared to all of the velocities that had occurred within the HOR study area at the time the fish had been detected. This was accomplished by comparing medians and by examining graphically the percentage of observations in velocity increments rounded to the nearest 0.05 m/s. Only velocity magnitude was considered (i.e., direction was not included in the analysis). Similar to the index of spatial use described above, an index of velocity occupied in relation to available velocity was calculated for each individual of each species; values greater than 1 suggested that fish occupied a particular velocity in greater proportion than its availability. As with the residence time and spatial analyses, statistical summaries of the data for each species were generated from 10,000 resamples of the velocity index results. Higher velocities that occurred only for some individuals within a given species were excluded from the analysis.



Sources: DWR 2012; Bianchini and Cane pers. comms., 2013; Present study; Data compiled by Turnpenny Horsfield Associates and AECOM in 2013

Figure 5-14

Spatial Zones Used in the Analysis of Predatory Fish and Predation at the Head of Old River

Emigration from the area of the HOR study area was determined for fish that left the study area before the deactivation of the acoustic array. Each fish was classified as having emigrated upstream (in the San Joaquin River) or downstream (into Old River or San Joaquin River) based on the final zone of detection. In addition to fish evaluated from 2009 through 2011, only the fish tagged and released to the upstream side of the 2012 rock barrier were included in this analysis.

Stationary Tag Locations

Information on spatial distribution of predatory fish at the HOR study area was provided by acoustic tagging (as described previously) and hydroacoustic surveys (as described under "Data Analysis" in Section 5.4.2, "Hydroacoustic Surveys"). Additional information on predator locations was obtained by examining the locations of stationary tags from juvenile salmonids. Stationary tags may represent juveniles that were preyed upon and subsequently defecated by predatory fish (or other predators) (Vogel 2011). Areas of high predation—or at least areas of high tag defecation—have been inferred from relatively high numbers of stationary tags, and include locations such as the trash racks leading to the Tracy Fish Facilities, Grant Line Canal, San Joaquin River near Stockton, and in some years, the HOR (SJRGA 2013).

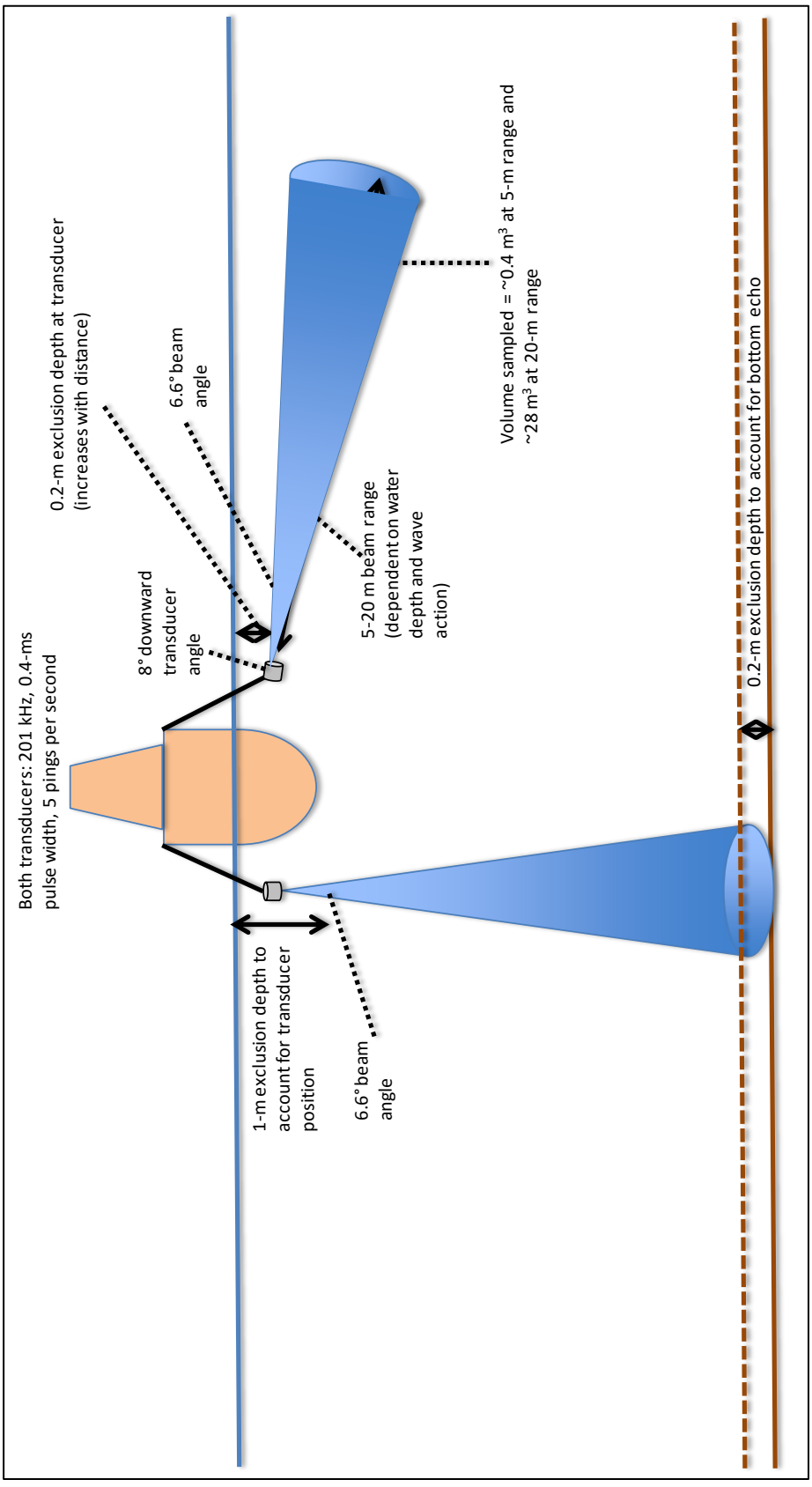
The locations of stationary salmonid tags at the HOR study area from 2009 through 2012 were plotted with GIS and enumerated by spatial zone, separating tags by salmonid species (Chinook salmon or steelhead) and year.

5.4.2 HYDROACOUSTIC SURVEYS

SURVEY METHODS

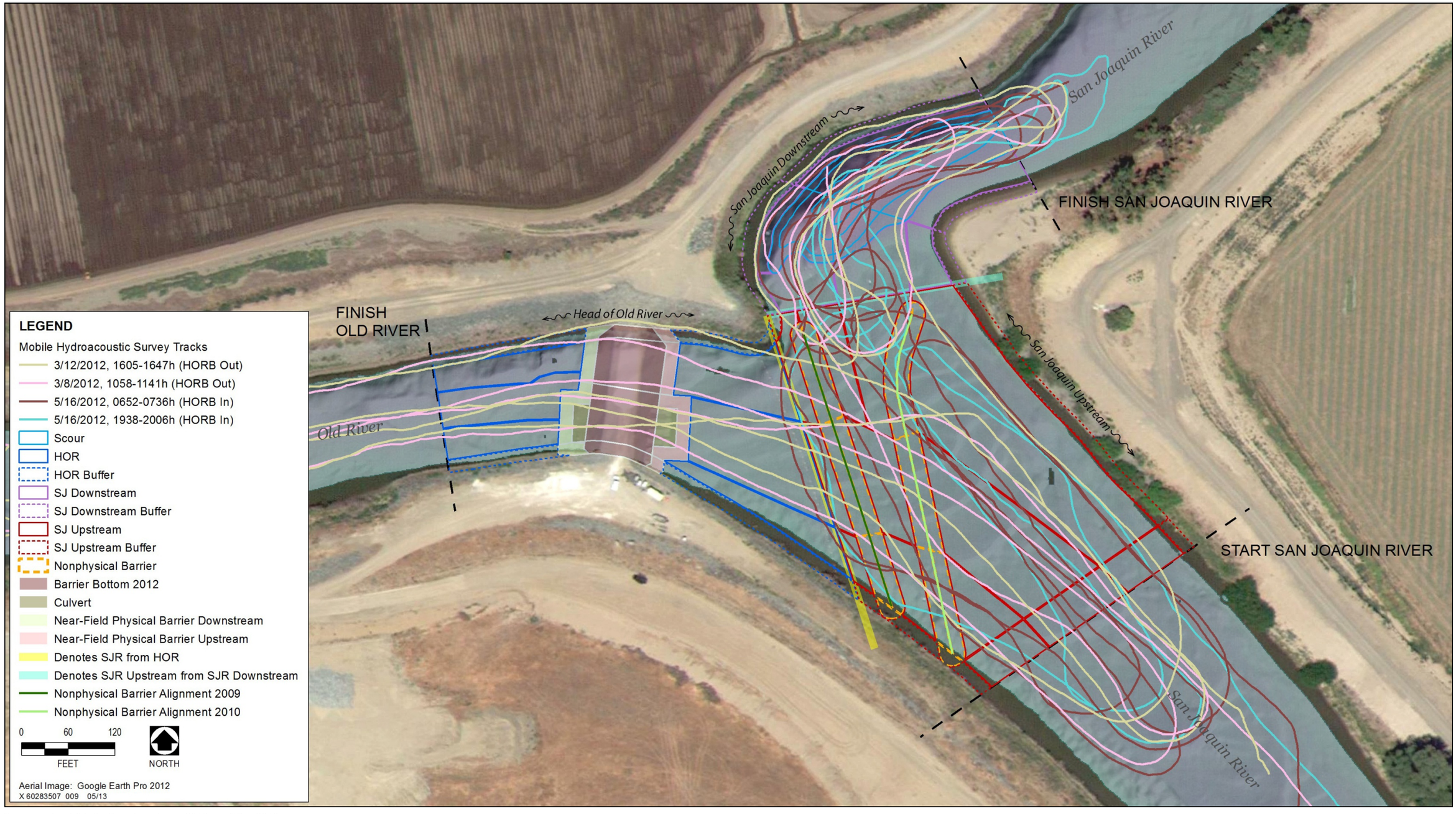
Mobile hydroacoustic surveys were conducted at the HOR study area to provide information on fish distribution and fluxes in fish density; surveys also were conducted at three reference sites. Mobile survey methods were similar to those used by Miranda et al. (2010) during the fish salvage facilities' Release Site Predation Study. Much of their description of the methods they used is provided herein. The acoustics unit employed for the mobile hydroacoustics survey was a BioSonics DT6000 split-beam system (BioSonics, Seattle, Washington). The unit employed two 201-kHz transducers, with one transducer mounted to point vertically down into the water column and the other mounted to point laterally off to the port side of the survey vessel (Figure 5-15). The acoustics unit used a -70-decibel (dB) threshold. A Wide Area Augmentation System-enabled E-Trex Vista (Garmin International, Olathe, Kansas) GPS unit was connected to the surface unit, and a location was recorded for each target detected.

Mobile hydroacoustic surveys consisted of driving the boat through the area of the HOR study area at a speed of approximately 7.2 km per hour (4.5 miles per hour). Surveys at the HOR study area typically lasted 30 to 40 minutes, and each individual survey covering all four sites generally lasted approximately 2 hours (Table 5-6). Nearly all surveys included sampling at all four sites. In 2011, sampling that yielded usable data was undertaken at the HOR study area during all 23 surveys (compared to 21 surveys for site 1 and 22 surveys for sites 2 and 4). In 2012, sampling that yielded usable data was undertaken on 26 of 29 surveys at the HOR study area (compared to 29 surveys for site 2, 27 surveys for site 1, and 28 surveys for site 4). Example survey paths from March and May 2012 are illustrated in Figure 5-16, with the physical rock barrier out and in, respectively.



Source: Present study.

Figure 5-15 **Schematic Diagram of Mobile Hydroacoustic Survey Equipment**



Sources: DWR 2012; ICF International 2013; AECOM 2013

Figure 5-16

Examples of Mobile Hydroacoustic Survey Tracks with Head of Old River Barrier In and Out

Table 5-6
Start and End Times of Mobile Hydroacoustics Surveys, 2011 and 2012

Survey Number	2011		2012	
	Start	End	Start	End
1	5/16/11, 16:30	5/16/11, 19:02	3/8/12, 9:14	3/8/12, 12:19
2	5/16/11, 20:03	5/16/11, 22:36	3/12/12, 13:40	3/12/12, 16:14
3	5/16/11, 23:25	5/17/11, 1:00	3/14/12, 13:56	3/14/12, 16:25
4	5/18/11, 7:46	5/18/11, 10:47	3/15/12, 6:44	3/15/12, 9:33
5	5/18/11, 11:52	5/18/11, 14:42	5/2/12, 6:48	5/2/12, 9:04
6	5/18/11, 17:36	5/18/11, 20:25	5/2/12, 9:18	5/2/12, 11:29
7	5/18/11, 21:16	5/18/11, 23:55	5/3/12, 8:55	5/3/12, 11:18
8	5/23/11, 7:56	5/23/11, 10:50	5/3/12, 12:17	5/3/12, 14:10
9	5/23/11, 11:49	5/23/11, 14:40	5/15/12, 6:43	5/15/12, 8:57
10	5/23/11, 18:34	5/23/11, 21:13	5/15/12, 10:22	5/15/12, 12:29
11	5/23/11, 21:57	5/24/11, 0:30	5/15/12, 16:50	5/15/12, 18:56
12	5/25/11, 7:49	5/25/11, 10:20	5/16/12, 4:41	5/16/12, 7:01
13	5/25/11, 11:09	5/25/11, 13:49	5/16/12, 9:55	5/16/12, 11:50
14	5/25/11, 18:30	5/25/11, 21:07	5/16/12, 17:35	5/16/12, 19:28
15	5/25/11, 21:56	5/26/11, 0:37	5/17/12, 4:42	5/17/12, 6:37
16	6/6/11, 14:26	6/6/11, 17:43	5/17/12, 10:28	5/17/12, 11:11
17	6/6/11, 18:28	6/6/11, 21:17	5/22/12, 4:55	5/22/12, 7:03
18	6/6/11, 21:53	6/7/11, 0:37	5/22/12, 8:36	5/22/12, 11:03
19	6/7/11, 9:02	6/7/11, 12:01	5/23/12, 4:28	5/23/12, 6:24
20	6/8/11, 9:19	6/8/11, 12:05	5/23/12, 6:41	5/23/12, 8:07
21	6/8/11, 12:23	6/8/11, 15:11	5/23/12, 17:42	5/23/12, 19:19
22	6/8/11, 18:59	6/8/11, 21:14	5/24/12, 4:42	5/24/12, 6:34
23	6/8/11, 21:35	6/9/11, 0:13	5/24/12, 6:49	5/24/12, 8:50
24			5/24/12, 11:28	5/24/12, 13:11
25			5/29/12, 15:34	5/29/12, 17:11
26			5/30/12, 4:18	5/30/12, 6:03
27			5/30/12, 13:30	5/30/12, 15:39
28			5/31/12, 4:41	5/31/12, 5:56
29			5/31/12, 6:50	5/31/12, 8:28

Source: Present study

Mobile hydroacoustic surveys also were conducted at three reference sites to provide comparisons to fish density at the HOR study area. The reference sites were on river bends and possessed deep holes somewhat similar to the HOR study area (Figure 5-17). A summary of water depths encountered by down-looking mobile hydroacoustic surveys in 2012 is provided in Table 5-7.

Table 5-7
Summary of Water Depths during Mobile Hydroacoustic Surveys in 2012

Statistic	Site 1		Site 2		HOR		Site 4	
	Meters	Feet	Meters	Feet	Meters	Feet	Meters	Feet
Minimum	0.7	2.4	0.9	2.8	0.9	3.0	0.8	2.7
5th Percentile	1.6	5.3	2.5	8.1	1.5	5.0	1.6	5.3
25th Percentile	2.5	8.1	4.1	13.3	2.3	7.4	2.3	7.5
Median	3.4	11.1	5.5	17.9	2.8	9.3	3.3	10.8
75th Percentile	5.6	18.5	6.7	21.9	4.3	14.0	4.5	14.9
95th Percentile	8.3	27.3	8.2	27.0	9.1	29.9	7.4	24.3
Maximum	10.0	32.7	10.5	34.5	11.6	38.2	8.2	26.8

Note: HOR = Head of Old River
Source: Present study

DATA ANALYSIS

Echo Counting/Processing

Echo counting methods following those described by Miranda et al. (2010) were used to measure acoustic target strength (fish size). The account herein was adapted from that of Miranda et al. (2010), and a useful introduction to fisheries acoustics is provided by Rudstam et al. (2012). Target strengths were measured using split-beam techniques for all sample locations. The target strength of a fish generally is related to the size of the fish, and is a measure of the capacity of a fish to reflect sound energy. Target strength, measured in units of decibels, is calculated from the energy reflected from the target, and is a function of the cross-sectional area of the target and the density difference between water and the component parts of the target (e.g., bones, scales, flesh, gas bladder).

Fish orientation, and to an extent species, can play a significant role in estimation of target size. The dB scale used to measure fish size is logarithmic and referenced in negative numbers (i.e., where the larger the negative number, the smaller the fish). Fish size was estimated from echo target strength using the following equation (Horn, pers. comm., 2013):

$$\text{Fish TL (cm)} = 1{,}529 * e^{(-0.1142 * |\text{Target Strength (dB)}|)}$$

Thus, for example, an echo intensity of -30 dB is estimated to be a fish of nearly 50 cm, whereas an echo intensity of -40 dB is estimated to be a fish just less than 16 cm. These sizes assume a transducer is looking down on a perfectly oriented fish from above. This is typically the case when looking down on a fish. When looking from the side, however, fish may not be perfectly oriented parallel to the transducer. When this occurs, a fish target will appear smaller than it actually is due to the reduced cross-sectional area of the target. Little can be done to rectify this problem.



Source: Present study

Figure 5-17

Locations of Head of Old River and Reference Mobile Hydroacoustic Survey Sites

The SonarData software package, Echoview v4.x (Myriax Software, Hobart, Tasmania, Australia) was used to analyze all data. The echogram was reviewed to locate individual fish targets, which were acquired and logged to data files. An amplitude threshold was used to reject echoes smaller than a predetermined voltage, and areas of high acoustic noise were manually removed from the raw echogram data prior to analysis by defining a line or region below which any data are ignored during the analysis phase (see Figure 38 in Miranda et al. 2010:87). Analyses of acoustic data consisted of a series of post-processing steps that are described in Appendix J of Miranda et al. (2010): observation, calibration and thresholding, regions for exclusion (noise), echo extraction, and output formatting/quality assurance. Considerable debris and acoustic noise within the system, as well as the study's emphasis on larger, potential predatory fish, led to the use of a target strength threshold of approximately 15 cm TL (i.e., approximately -40 dB), with fish less than this size being excluded from the data outputs.

The number of targets (assumed to be fish) detected, mean target strength, and beam volume sum were output into a number of "bins" of information from each survey at each site. Data from 2011 were output into bins of 200 pings, whereas data from 2012 were output into bins of 100 pings. Potential predator-sized targets were assessed to be those estimated to be greater than 30 cm TL for consistency with sizes of predatory fish studied with acoustic tagging (see "Field Methods" in Section 5.4.1, "Predatory Fish Acoustic Tagging"). Analyses focused on the targets that measured greater than 30 cm TL, with other fish being binned into a 15- to 30-cm TL size class. In addition to binned outputs, data on each individual target were output, and included target strength (fish size), location (latitude/longitude), target water depth, and total water column depth (for down-looking hydroacoustic data).

Statistical Methods

Areas Occupied

Data derived from mobile hydroacoustic surveys in 2011 and 2012 were used to address several of the study objectives. GIS plots of individual targets (estimated to be greater than 30 cm TL) were made to illustrate fish distribution within the study area, particularly with respect to habitat features such as the scour hole. The number of targets from down- and side-looking transducers were summed for each spatial zone.

Density Changes

Changes of greater than 30 cm TL fish density (abundance per unit volume) at the HOR study area in 2011 and 2012 were examined in relation to several environmental variables that could influence density and that were included in the analysis of probability of predation of juvenile salmonids: water temperature, discharge, turbidity, light level, and small fish density. Features of the environmental data are summarized in Table 5-8. Abiotic habitat variables such as water temperature have been shown to correlate with movements and behavior of predatory fish such as striped bass (e.g., upstream movement in spring for spawning purposes; Moyle 2002). Biotic variables such as prey fish density have also been hypothesized to influence striped bass distribution (e.g., predators moving to areas where prey are relatively abundant; LeDoux-Bloom 2012). For some predatory fish species such as largemouth bass, habitat suitability may be inversely related to river discharge and channel velocity (Stuber et al. 1982).

Table 5-8
Summary of Predictor Variables Used in GLM of Abundance of Fish Greater than 30 cm TL at the Head of Old River Study Area

Variable (Unit)	Location	Source	Transformation	Notes
Water Temperature (°C)	SJL	CDEC (Baldwin, pers. comm., 2013)	None	15-minute average data
River Discharge (m^3/s)	SJL	CDEC (Baldwin, pers. comm., 2013)	None	15-minute average data
Turbidity (NTU)	MSD	CDEC (Dempsey, pers. comm., 2013)	None	15-minute average data
Ambient light (lux)	Manteca (CIMIS site #70)	CIMIS (State of California 2009)	Natural logarithm + 1	Original CIMIS data (Langley/day) were first converted into PAR per Clark et al. (2009: PAR, $\mu mol/m^2/s$ = 1.1076*Langley/day), and subsequently PAR was converted into lux per Apogee Instruments, Inc. (2013: Lux = 54*PAR). Original hourly data were linearly interpolated to 15-minute increments for consistency with water quality data.
Small-fish density (fish < 15 cm FL/10,000 m^3)	Mossdale (trawling)	USFWS survey data (Speegle, pers. comm., 2011 and 2013)	Natural logarithm + 1	

Notes: °C = degrees Celsius; CDEC = California Data Exchange Center; CIMIS = California Irrigation Management Information System; cm = centimeters; m^3 = cubic meters; m^3/s = cubic meters per second; MSD = San Joaquin River at Mossdale; NTU = nephelometric turbidity units; PAR = photosynthetically active radiation; SJL = San Joaquin River at Lathrop; USFWS = U.S. Fish and Wildlife Service
Source: Present study

In contrast to the analysis of predation probability, however, the analysis of changes in predatory fish density (as represented by density of echoes greater than 30 cm TL) in relation to environmental variables was more of an exploratory analysis that relied on a model-averaging approach to examine support for the influence of the different variables on predatory fish density. Accordingly, the analysis was conducted to test the null hypothesis $H14_0$ (see "Objectives and Hypotheses Related to Changes in Density of Predatory Fishes" in Section 1.2.4, "Behavior and Density Changes in Predatory Fishes").

The analysis of changes in density in relation to environmental variables was conducted with GLM within a model averaging/information theoretic framework similar to that used for modeling predation probability of juvenile salmonids (see Section 5.3.2, "Probability of Predation [Generalized Linear Modeling]"). The number of fish targets greater than 30 cm TL in each survey at the HOR study area was modeled in the GLM as a count response variable with a negative binomial error structure and logarithmic link function, incorporating the beam volume sum as an offset to account for differences in the volume of water ensonified with the acoustic equipment during each survey.

The glmulti package was used to provide all possible first-order GLMs for fish targets greater than 30 cm TL as a function of water temperature, discharge, turbidity, light, and small-fish density (i.e., a measure of potential prey for predatory fish). The relative level of support for each possible model was estimated in glmulti with the quasi-

likelihood equivalent of AIC corrected for small sample sizes ($QAIC_c$) (Mazerolle 2006). The variance inflation factor, $\hat{c}$, required to compute $QAIC_c$ was estimated by initially running a single GLM with all predictor variables included, and then providing $\hat{c}$ to the glmulti package for the automated model averaging procedure. The difference in $QAIC_c$, Δ_i, between each model and the best model (i.e., the model with the lowest $QAIC_c$) was calculated, and Akaike weights (w_i) were calculated based on the Δ_i. Model averaging of the predictor variable coefficients was undertaken based on the Akaike weights for each model, and unconditional confidence intervals were calculated for each coefficient (Mazarolle 2006). The importance of each predictor variable was assessed by summing the w_i of all models in which the variable appeared. Following Calcagno and de Mazancourt (2010), importance of 0.8 or greater was used to infer support for a variable's potential influence on greater than 30-cm fish density, in addition to unconditional 95% confidence intervals for variable coefficients not overlapping zero (per Zeug and Cavallo 2013). GLMs, including predictors, were assessed to provide a better fit to the data than intercept-only models if the $QAIC_c$ of the full models (with all predictors included) was 3 or more units greater than the $QAIC_c$ of the intercept-only models (Zeug and Cavallo 2013).

Four sets of GLM analyses were included, with two each for the down-looking and side-looking greater than 30-cm fish density data. "Same-day" GLM analyses used water quality and light variables that were averaged based on the time that the survey had occurred at the HOR study area (e.g., if a survey took place between 0500 and 0545 hours, the water quality data and light data were the average values for this time period).

The small-fish density data variable from Mossdale trawling was based on the mean daily densities from the day of the mobile hydroacoustic survey and the previous 2 days (see description of calculation of abundance index in Section 2.2.3, "River Channel Mossdale Trawl"), because trawling did not necessarily occur daily and it was desirable to retain all mobile hydroacoustic survey data points. (The 3-day-average small-fish density avoided censoring of mobile hydroacoustic data because of missing data.) It was felt that this was a reasonable approach to provide a general indication of small-fish (potential prey) density in the area at the time of the mobile hydroacoustic surveys, given that the Mossdale trawl site is upstream of the HOR study area, and there would be some delay in fish reaching the HOR study area, coupled with natural variability in these data.

The "7-day" GLM analyses used water-quality and small-fish-density data averaged over the time of the mobile hydroacoustic survey and the 6 days. These analyses were included to account for potential longer-term environmental influences on greater than 30-cm fish density at the HOR study area. Light data for the GLM analyses were identical to those for the "same-day" analyses because light level was hypothesized only to be a short-term potential influence on density.

Comparisons to Reference Sites

The HOR study area was compared to the three reference sites to assess whether changes in greater than 30-cm fish density were correlated and to assess the evidence for common environmental influences on fish density (e.g., migration). Density (number of targets per 10,000 cubic meters) of greater than 30-cm fish from each survey at the HOR study area were paired with corresponding densities from the same survey at each reference site. Density data were incremented by 1 to account for 0 values and natural-log-transformed to accommodate the assumptions of the parameter statistical tests. Pearson correlation analyses were used to test the null hypothesis $H15_0$ (see "Objectives and Hypotheses Related to Density of Predatory Fishes" in Section 1.2.4, "Behavior and Density Changes in Predatory Fishes") of no significant correlation between density at the HOR study area with density at each reference site. A Bonferroni-adjusted statistical significance of $P < 0.017$ was used to correct for

the three comparisons. The null hypothesis $H16_0$ of no significant difference in density between the HOR study area and the reference sites was tested using paired t-tests. Statistical analyses comparing the HOR study area to the reference sites were undertaken with SAS/STAT software, Version 9.3, of the SAS System for Windows.[2]

Diel Changes in Depth

Fish depth is of management interest because it influences capture methods that can be used for predatory fish. Fish are often found deeper in the water column by day (Hrabik et al. 2006; Miranda et al. 2010). In addition, large densities of common carp were visually observed in the vicinity of the physical rock barrier in 2012, suggesting that many large-fish targets detected with mobile hydroacoustics may not be predatory fish. Common carp are omnivorous bottom feeders (Moyle 2002) that would be expected to be associated with the bottom at all times of day. Depth of greater than 30-cm TL targets from down-looking mobile hydroacoustic surveys was examined in relation to total water column depth for evidence of changes in distribution with diel period. Following Hrabik et al. (2006), plots of individual target depth against distance from the bottom (based on water column depth) were made to assess differences between day, night, dawn, and dusk. Day was defined as greater than 1 hour after sunrise and before sunset, dawn was the 2-hour period centered around sunrise, dusk was the 2-hour period centered around sunset, and night was greater than 1 hour after sunset and before sunrise. Sunrise and sunset times were estimated for SJL using the National Oceanic and Atmospheric Administration's sunrise/sunset spreadsheet calculator (NOAA 2013).

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6 RESULTS

6.1 JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

6.1.1 2009 RESULTS

SALMONID SIZE DISTRIBUTION

The juvenile Chinook salmon tagged and released in 2009 were smaller overall than those from any other year (Table 5-1). In addition, the tagged 2009 juvenile Chinook salmon were Feather River Fish Hatchery fall-spring–run hybrids; 2009 was the only year when this hatchery and these hybrids were used as a source of juvenile Chinook salmon.

OVERALL EFFICIENCY

Chinook Salmon

The data were evaluated to determine whether they satisfied the assumptions of ANOVA. In every case, except as noted in the following discussion, the data were not distributed normally and/or did not meet the assumption of homogeneity of variances. In general, the lack of normally distributed data stemmed from the common occurrence of 0.0 and 1.0 values in the samples. These categories tended to be among the most common values observed which resulted in many variables exhibiting a bimodal distribution.

The overall efficiency (O_E) was only 2.5 percentage points better with the BAFF on than off (Table 6-1). Only 20.9% of tags in juvenile Chinook salmon continued down the San Joaquin River with the BAFF on, compared with 18.4% with the BAFF off. These results suggested that the BAFF did not significantly change the proportion of fish remaining in the San Joaquin River in 2009 (i.e., hypothesis $H1_0$ was accepted).

Table 6-1
Statistics for Overall Efficiency during BAFF Operations in 2009

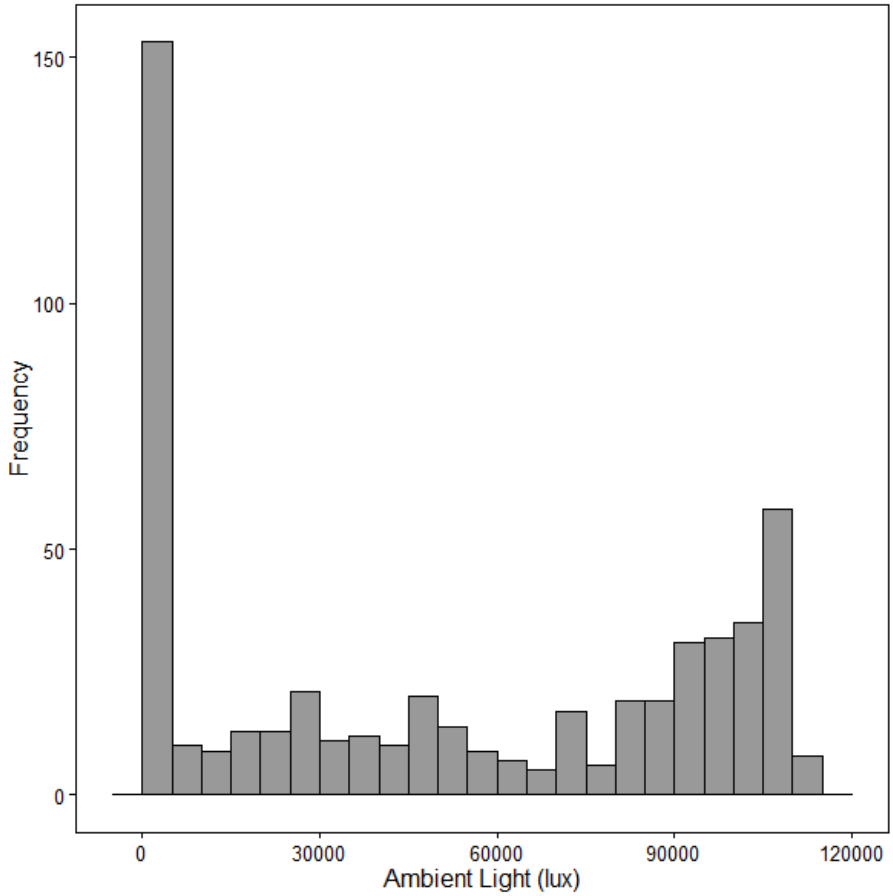
Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^2	P-value
Mean	0.209	0.184	2.5	0.030	0.8635
Standard Deviation	0.218	0.185			
Minimum	0.000	0.000			
Maximum	0.750	0.500			
Samples (n)	21	27			

Notes: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Ambient Light Level on Overall Efficiency

Tagged juvenile Chinook salmon approached the 2009 BAFF line at various light levels (Figure 6-1). When the 2009 fish were placed into samples, and the juvenile Chinook salmon O_E samples were partitioned by ambient light

level, eight to 17 samples were distributed throughout the experimental matrix (Table 6-2). For high-ambient-light conditions, it was noted that O_E with the BAFF on was 9.9 percentage points higher than with the BAFF off (Table 6-3). However, there was no significant improvement in O_E with the BAFF on compared to off at either ambient light level. In 2009, it appeared that there was insufficient statistical power to resolve any effect or ambient light did not influence the BAFF's O_E.



Source: Data compiled by AECOM and Turnpenny Horsfield Associates

Figure 6-1 Frequency Histogram of 2009 Light-Level Observations (collected at CIMIS, Station #70–Manteca, 37.834822, -121.223194) Obtained for Each Tagged Juvenile Chinook Salmon when the Individual was Nearest the 2009 BAFF Line

Table 6-2
Summary of Overall Efficiency Samples for Tagged Juvenile Chinook Salmon Encountering the BAFF during On/Off Operations at Low and High Ambient Light Levels in 2009

Ambient Light Level	BAFF On (n)	BAFF Off (n)
Low Light (<5.4 lux)	8	10
High Light (≥5.4 lux)	13	17
Total	21	27

Notes: BAFF = bio-acoustic fish fence; n = number of overall efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

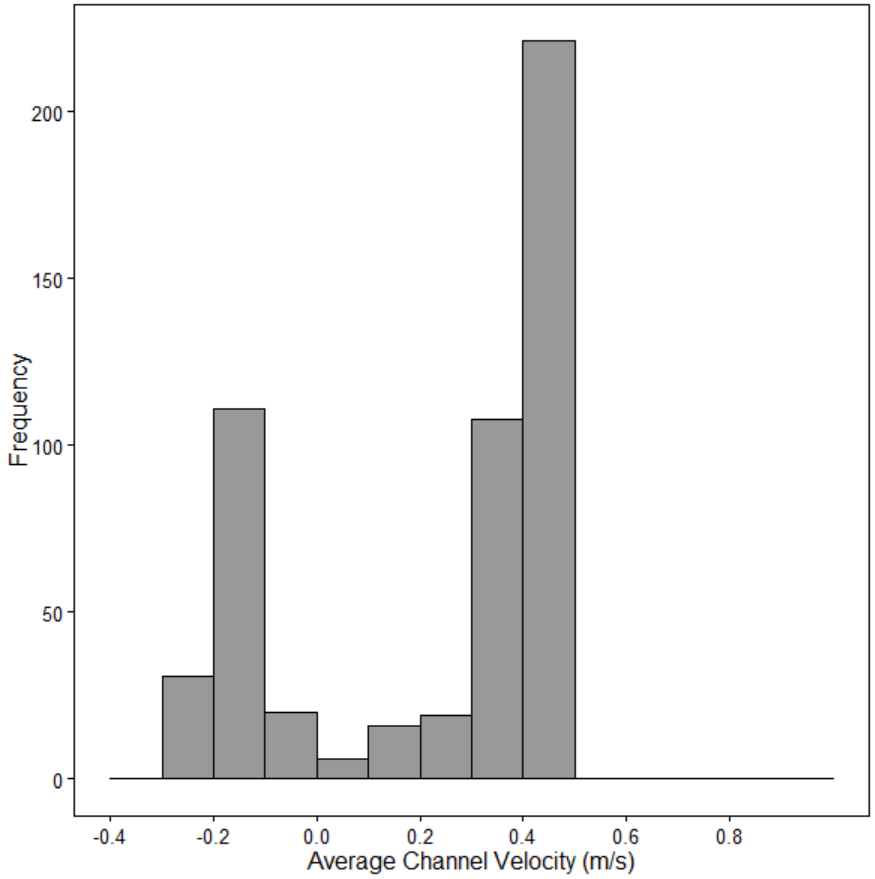
Table 6-3
Mean Overall Efficiency of the BAFF for Tagged Juvenile Chinook Salmon at Low and High Ambient Light Levels in 2009

Overall Efficiency—Ambient Light Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-value
Low Light (<5.4 lux)	0.068	0.159	-9.1	0.772	0.3797
High Light (≥5.4 lux)	0.297	0.198	9.9	1.131	0.2876

Notes: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Average Channel Velocity on Overall Efficiency

Tagged juvenile Chinook salmon approached the 2009 BAFF line at various average channel velocities (ACV) (Figure 6-2). When the 2009 fish were placed into samples and the O_E samples for juvenile Chinook salmon were partitioned by ACV value (low = less than 0.61 m/s ACV; high = greater than or equal to 0.61 m/s ACV), no samples existed at high ACV values (Figure 6-2). This result was expected because in 2009 the water year had the lowest discharge range and mean among the years studied. The maximum ACV recorded during the tagged juvenile Chinook salmon release period was 0.48 m/s.



Source: Data compiled by AECOM and Turnpenny Horsfield Associates

Figure 6-2 **Frequency Histogram of 2009 Average Channel Velocity Observations (SJL Gauge) Obtained for Each Tagged Juvenile Chinook Salmon when the Individual was Nearest the 2009 BAFF Line**

PROTECTION EFFICIENCY

BAFF protection efficiency (P_E) (efficiency after the removal from the data set of juvenile Chinook salmon that were eaten) was 0.234 with the BAFF off. The proportion of flow into the San Joaquin River during the study period was 0.35 (Table 3-1). Thus, in the present study, without the BAFF in operation, the fraction of juvenile Chinook salmon was smaller than the fraction of water entering the San Joaquin River. In contrast, in Table I-1 in Appendix I, "Route Entrainment Analysis at Head of Old River, 2009 and 2010," the proportion of flow entering the San Joaquin River was correlated with the probability that an individual juvenile Chinook salmon would continue down the San Joaquin River route. The model that included flow at the San Joaquin River at Lathrop (SJL) gauge fit the data better than did the proportion of flow into the San Joaquin River (Table I-2 in Appendix I).

P_E was 10.4 percentage points better with the BAFF on than with the BAFF off, but this result was not significant (Table 6-4) (i.e., hypothesis $H1_0$ was accepted). However, a comparison of Tables 6-1 and 6-4 showed that with "tagged juvenile Chinook determined to have been eaten" removed, the BAFF-on performance improved from an O_E of 20.9% to a P_E of 33.8%. These results showed that the BAFF maintained juvenile Chinook salmon in the San Joaquin River at a proportion (0.338) similar to the fraction of water entering the San Joaquin River (0.35) at the HOR study area. The GLM presented in Appendix I showed that with the BAFF on, there was a greater probability (P = 0.0010) that a juvenile Chinook salmon would enter the San Joaquin River route (Table 7-1 in Appendix I).

Table 6-4
Statistics for Protection Efficiency during BAFF Operations in 2009

Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.338	0.234	10.4	0.669	0.4133
Standard Deviation	0.330	0.220			
Minimum	0.000	0.000			
Maximum	1.000	0.667			
Samples (n)	18	25			

Notes: BAFF = bio-acoustic fish fence; n = number of protection efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Ambient Light Level on Protection Efficiency

When the samples for 2009 BAFF P_E were partitioned by ambient light level (Table 6-5), seven to 16 samples were found for various combinations of BAFF operations with ambient light levels. For high-ambient-light levels, it was noted that BAFF P_E with the BAFF on was 21.9 percentage points higher than with the BAFF off (Table 6-6); the statistical power of the test was only 0.435. In addition, there was no improvement in P_E with the BAFF on compared to the BAFF off at either ambient light level. In 2009, it appeared that there was insufficient power to resolve any effect, or ambient light did not influence BAFF P_E.

Table 6-5
Summary of Protection Efficiency Samples for Tagged Chinook Salmon Encountering BAFF during On/Off Operations at Low and High Light Levels in 2009

Ambient Light Level	BAFF On (n)	BAFF Off (n)
Low Light (<5.4 lux)	7	9
High Light (≥5.4 lux)	11	16
Total	18	25

Notes: BAFF = bio-acoustic fish fence; n = number of protection efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-6
2009 BAFF Operations—Mean Protection Efficiency for Chinook Salmon at Low and High Light Levels

Ambient Light Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-value
Low Light (<5.4 lux)	0.108	0.178	-7.0	0.720	0.3960
High Light (≥5.4 lux)	0.484	0.265	21.9	3.126	0.0771

Notes: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Average Channel Velocity on Protection Efficiency

No samples were acquired under high-ACV conditions in 2009. Thus, sample sizes and means under low-velocity conditions were the same as those shown in Table 6-4.

DETERRENCE EFFICIENCY

For deterrence efficiency (D_E), some tags were removed for the calculation. If a tag was determined to have been eaten before it experienced the BAFF, then it was not included. D_E with the BAFF on showed a significant improvement (Kruskal-Wallis $X^2 = 11.398$, $P = 0.007$), 2.35 times greater, than D_E with the BAFF off (Table 6-7). Hypothesis $H1_0$ was rejected for D_E. It appeared that the BAFF was effective at deterring juvenile Chinook salmon when individuals approached the BAFF.

Table 6-7
Deterrence Efficiency Statistics for BAFF Operations in 2009

Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.732	0.311	42.1	11.398	0.0007
Standard Deviation	0.335	0.322			
Minimum	0.000	0.000			
Maximum	1.000	1.000			
Samples (n)	18	23			

Notes: BAFF = bio-acoustic fish fence; n = number of deterrence efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

The D_E with the BAFF off was 31.1%. This is the percentage of fish that exhibited movements that appeared to be movements away from the BAFF and toward the San Joaquin River, or movements of a fish guided along the line of, and past the end of, the BAFF. These movements may have occurred because the BAFF infrastructure took up some proportion of the water column, which may create turbulence or reflect ambient light. It is possible that a proportion of the fish would sense the turbulence created by the BAFF infrastructure or see ambient light reflected from barrier components and would move away from it or be guided along it.

The mean D_E with the BAFF on was 73.2% in the 2009 analysis reported. This is slightly less than the grand D_E reported in Bowen et al. (2012) of 81.4%. This difference arose from the reanalysis of the deterrence data in the present study because fish were placed into samples from the same time period with similar ambient light and ACV values when the fish arrived at the HOR study area (see definition of samples in Chapter 5, "Methods") instead of being placed in groups that were associated with the release date/time.

Effect of Ambient Light Level on BAFF Deterrence Efficiency

When the samples for 2009 BAFF D_E were partitioned by ambient light level (Table 6-8), seven to 15 samples were found for various combinations of BAFF operations and ambient light levels. For high-ambient-light conditions, it was noted that D_E with the BAFF on was 52.7 percentage points higher than with the BAFF off (Table 6-9), and this difference was significant. This result was consistent with the laboratory study of a BAFF by Bowen et al. (2009), which found the highest D_E for juvenile Chinook salmon occurred during the day and at the lower turbidity condition studied: 10 NTU. The lowest mean turbidity in the HOR study area of all the years studied, 19.9 NTU (Table 3-4), occurred in 2009.

Table 6-8
Summary of Deterrence Efficiency Samples for Tagged Juvenile Chinook Salmon Encountering BAFF during On/Off Operations at Low and High Light Levels in 2009

Ambient Light Level	BAFF On (n)	BAFF Off (n)
Low Light (<5.4 lux)	7	8
High Light (≥5.4 lux)	11	15
Total	18	23

Notes: BAFF = bio-acoustic fish fence; n = number of deterrence efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-9
2009 BAFF Operations—Mean Deterrence Efficiency for Tagged Juvenile Chinook Salmon at Low and High Light Levels

Ambient Light Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-value
Low Light (<5.4 lux)	0.474	0.202	27.2	2.330	0.1269
High Light (≥5.4 lux)	0.897	0.370	52.7	12.448	0.0004

Notes: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

There was an improvement of 27.2% in D_E with the BAFF on compared to operations with the BAFF off at low ambient light levels (Table 6-9). However, this result was not significant. In 2009, it was concluded that the BAFF delivered juvenile Chinook salmon deterrence (Table 6-9), and that the performance of the BAFF was the best at high ambient light magnitudes, in contrast to the findings of Welton et al. (2002), who found the highest proportion deflected at night.

Effect of Average Channel Velocity on Barrier Deterrence Efficiency

In 2009, all samples were categorized as "low velocity," where ACV is less than 0.61 m/s (= Approach Velocity <0.25 m/s). Thus, no comparisons of D_E at various ACV ranges were possible.

6.1.2 2010 RESULTS

SIZE AND SOURCE OF JUVENILE CHINOOK SALMON USED

The juvenile Chinook salmon tagged and released in 2010 were similar in size to those from 2011 and 2012, and larger than those from 2009 (Table 5-1). In 2010, and in all subsequent years of the research reported herein, the Merced River Hatchery was the source of juvenile Chinook salmon.

OVERALL EFFICIENCY

Chinook Salmon

The O_E for the BAFF was only 11.0 percentage points higher with the BAFF on than with the BAFF off, which was not statistically significant (Table 6-10); hypothesis $H2_0$ was accepted.

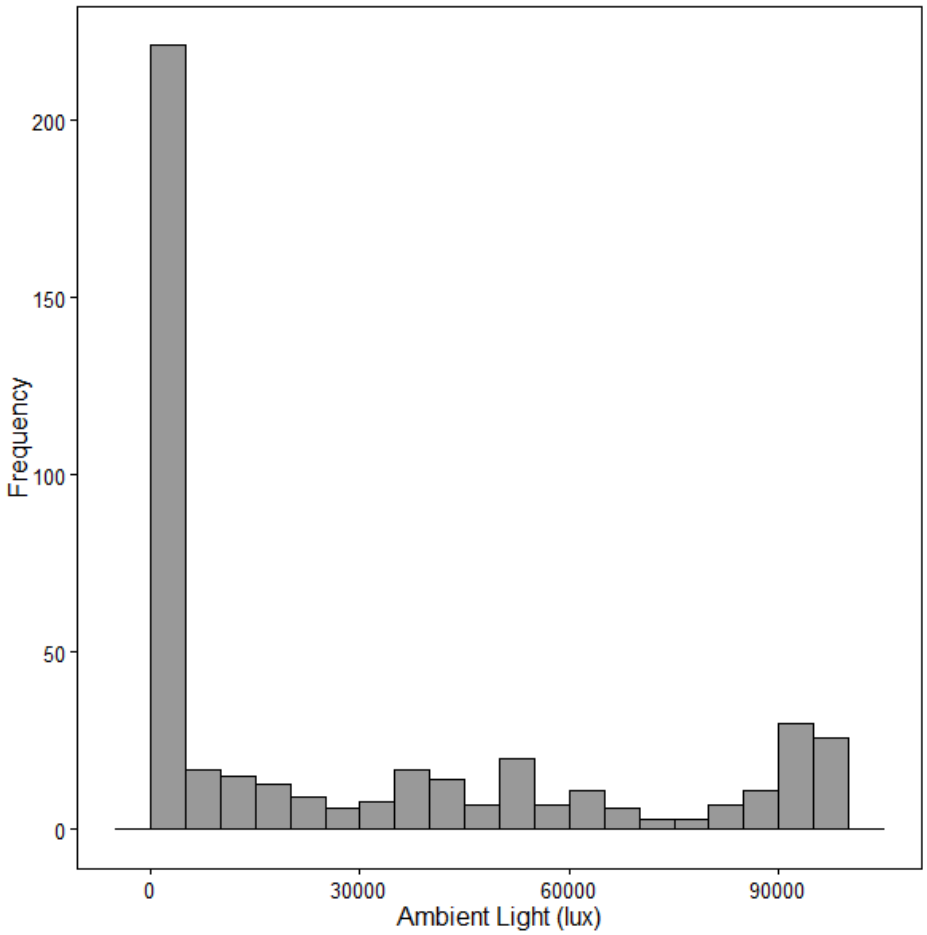
Table 6-10
Statistics for Overall Efficiency during BAFF Operations in 2010

Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^2	P-value
Mean	0.355	0.245	11.0	1.392	0.2380
Standard Deviation	0.243	0.183			
Minimum	0.000	0.000			
Maximum	1.000	0.500			
Samples (n)	19	22			

Notes: BAFF = bio-acoustic fish fence; n = number of overall efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Ambient Light Level on Overall Efficiency

Tagged juvenile Chinook salmon approached the 2010 BAFF line at various light levels (Figure 6-3). When the 2010 juvenile Chinook salmon were placed into samples, and the O_E samples were partitioned by light level, nine to 12 samples were acquired in the BAFF status and light level combinations (Table 6-11). For low-light levels, mean O_E with the BAFF on was 19.1 percentage points higher than with the BAFF off (Table 6-12), but there was no improvement in O_E with the BAFF on compared to off at either light level. In 2010, it appeared that there was insufficient statistical power to resolve any effect, or light level did not influence the BAFF's O_E.



Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Figure 6-3 Frequency Histogram of 2010 Light-Level Observations (collected at CIMIS, Station #70–Manteca, 37.834822, -121.223194) Obtained for Each Tagged Juvenile Chinook Salmon when the Individual was Nearest the 2010 BAFF Line

Table 6-11
Summary of Overall Efficiency Samples for Tagged Juvenile Chinook Salmon Encountering BAFF during On/Off Operations at Low and High Ambient Light Levels in 2010

Ambient Light Level	BAFF On (n)	BAFF Off (n)
Low Light (<5.4 lux)	9	12
High Light (≥5.4 lux)	10	10
Total	19	22

Notes: BAFF = bio-acoustic fish fence; n = number of overall efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-12
2010 BAFF Operations—Mean Overall Efficiency for Tagged Juvenile Chinook Salmon at Low and High Light Levels

Ambient Light Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Light (<5.4 lux)	0.506	0.315	19.1	2.155	0.1421
High Light (≥5.4 lux)	0.219	0.161	5.8	1.379	0.2403

Note: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Average Channel Velocity on Overall Efficiency

Tagged juvenile Chinook salmon approached the 2010 BAFF line at various light levels (Figure 6-4). When the 2010 fish were placed into samples and the O_E samples for juvenile Chinook salmon were partitioned by ACV level, only four samples were acquired for high-velocity conditions for both the BAFF on and off (Table 6-13). For low-velocity conditions, mean O_E with the BAFF on was 11.9 percentage points higher than with the BAFF off (Table 6-14), but there was no significant improvement in O_E with the BAFF on compared to off at either ACV level. In 2010, it appeared that there was insufficient statistical power to resolve any effect or ACV did not influence the BAFF's O_E.

Table 6-13
Summary of Overall Efficiency Samples for Tagged Juvenile Chinook Salmon Encountering BAFF during On/Off Operations at Low and High Average Channel Velocity Levels in 2010

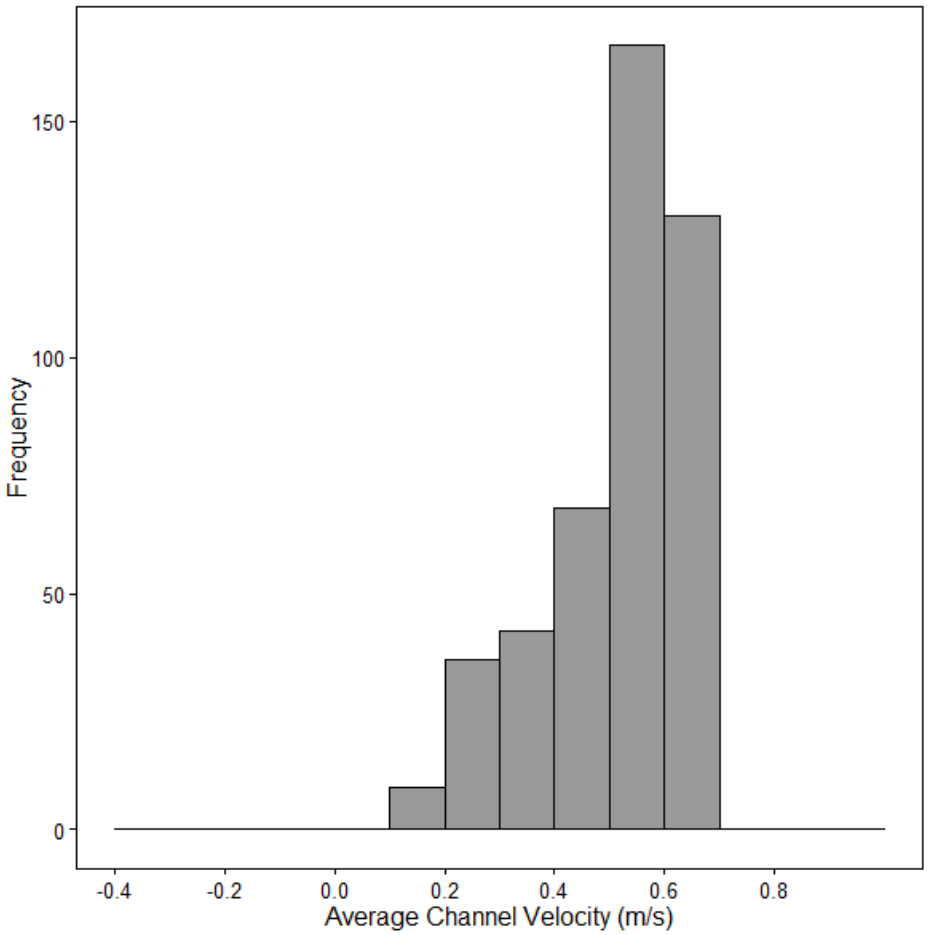
Average Channel Velocity Level	BAFF On (n)	BAFF Off (n)
Low Velocity (<0.61 m/s)	15	18
High Velocity (≥0.61 m/s)	4	4
Total	19	22

Notes: BAFF = bio-acoustic fish fence; n = number of overall efficiency samples; m/s = meters per second; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-14
2010 BAFF Operations—Mean Overall Efficiency for Tagged Juvenile Chinook Salmon at Low and High Average Channel Velocity Levels

Average Channel Velocity Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Velocity (<0.61 m/s)	0.352	0.233	11.9	1.479	0.2240
High Velocity (≥0.61 m/s)	0.367	0.298	6.9	0.021	0.8845

Notes: BAFF = bio-acoustic fish fence; m/s = meters per second
Source: Data compiled by Turnpenny Horsfield Associates and AECOM



Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Figure 6-4 Frequency Histogram of 2010 Average Channel Velocity Observations (SJL Gauge) Obtained for Each Tagged Juvenile Chinook Salmon when the Individual was Nearest the 2010 BAFF Line

PROTECTION EFFICIENCY

BAFF P_E was 0.286 with the BAFF off, and the proportion of flow into the San Joaquin River during the study period was 0.56 (Table 3-1). Similar to 2009, the proportion of juvenile Chinook salmon entering the San Joaquin River in 2010 was not the same as the proportion of flow. The fraction was lower. In contrast, in Table 7-3 in Appendix I, the proportion of flow entering the San Joaquin River was correlated (P = 0.0003) with the probability that an individual juvenile Chinook salmon would continue down the San Joaquin River route. The multivariate analysis showed that the proportion of flow into the San Joaquin River (SJL gauge), and ACV models fit the data equally well (Table 7-2 in Appendix I). All analyses showed correlation with the probability that a juvenile Chinook salmon would be entrained into the San Joaquin River route.

P_E was 15.5 percentage points higher with the BAFF on than with the BAFF off and, in contrast to 2009, this result was statistically significant (Table 6-15). Hypothesis $H2_0$ was rejected. It was found that 44.1% of tagged juvenile Chinook salmon continued down the San Joaquin River with the BAFF on. These results showed that the BAFF improved the proportion of juvenile Chinook salmon remaining in the San Joaquin River in 2010, but it is unknown whether this improvement was biologically significant at the population level. These results were

consistent with the GLM presented in Appendix I. It showed that with the BAFF on a greater probability (P = 0.0002) existed that a juvenile Chinook salmon would enter the San Joaquin River route (Table 7-3 in Appendix I).

Table 6-15
Statistics for Protection Efficiency during BAFF Operations in 2010

Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.441	0.286	15.5	3.943	0.0471
Standard Deviation	0.239	0.206			
Minimum	0.000	0.000			
Maximum	1.000	0.667			
Samples (n)	19	20			

Notes: BAFF = bio-acoustic fish fence; n = number of protection efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Ambient Light Level on Protection Efficiency

When the samples for 2010 P_E were partitioned by ambient light level (Table 6-16), nine to 10 samples were found for various combinations of BAFF operations with ambient light levels. For low-ambient-light levels, mean P_E with the BAFF on was 16.7 percentage points higher than off (Table 6-17). For high-ambient-light levels, mean P_E with the BAFF on was 15.3 percentage points higher than with the BAFF off, the P_E test provided a P value of 0.0812 and a statistical power of just 0.417. It appeared that it may not have been possible to reject a false null hypothesis because of the low power of the test. As in 2009, at both low and high light levels, there was no statistically significant improvement in P_E with the BAFF on compared to off. In 2010, it appeared that there was insufficient power to resolve any effect, or light level did not influence the BAFF's P_E.

Table 6-16
Summary of Protection Efficiency Samples for Tagged Juvenile Chinook Salmon Encountering BAFF during On/Off Operations at Low and High Light Levels in 2010

Ambient Light Level	BAFF On (n)	BAFF Off (n)
Low Light (<5.4 lux)	9	10
High Light (≥5.4 lux)	10	10
Total	19	20

Notes: BAFF = bio-acoustic fish fence; n = number of protection efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-17
2010 BAFF Operations—Mean Protection Efficiency for Juvenile Chinook Salmon at Low and High Light Levels

Ambient Light Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Light (<5.4 lux)	0.526	0.359	16.7	1.513	0.2186
High Light (≥5.4 lux)	0.365	0.212	15.3	3.041	0.0812

Notes: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Average Channel Velocity on Protection Efficiency

When the samples for 2010 P_E were partitioned by ACV level only, four samples were acquired for high-ACV conditions for both BAFF on and off (Table 6-18) status. For low-ACV conditions, P_E with the BAFF on was 16.9 percentage points higher than off (Table 6-19), but there was no statistically significant improvement in P_E with the BAFF on compared to off at either velocity level. These results suggested that there may have been insufficient power to resolve any effect, or ACV did not influence the BAFF's P_E. However, the P-value for low ACV was 0.0544 but the statistical power of this test was only 0.544. It appears that more research in this area would be useful.

Table 6-18
Summary of Protection Efficiency Samples for Tagged Juvenile Chinook Salmon Encountering BAFF during On/Off Operations at Low and High Average Channel Velocity Levels in 2010

Average Channel Velocity Level	BAFF On (n)	BAFF Off (n)
Low Velocity (<0.61 m/s)	15	16
High Velocity (≥0.61 m/s)	4	4
Total	19	20

Notes: BAFF = bio-acoustic fish fence; n = number of protection efficiency samples; m/s = meters per second
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-19
2010 BAFF Operations—Mean Protection Efficiency for Tagged Juvenile Chinook Salmon at Low and High Average Channel Velocity Levels

Average Channel Velocity Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Velocity (<0.61 meter per second)	0.435	0.266	16.9	3.699	0.0544
High Velocity (≥0.61 meter per second)	0.465	0.365	10.0	0.527	0.4678

Notes: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

DETERRENCE EFFICIENCY

The BAFF-on treatment showed an improvement (Kruskal-Wallis $X^2 = 13.095$, $P = 0.0003$) in D_E: 13.8 percentage points greater than with the BAFF off (Table 6-20). Thus, hypothesis $H2_0$ was rejected. The analysis showed that the BAFF provided a statistically significant deterrent for diverting juvenile Chinook salmon when an individual approached the BAFF. It is unknown whether this level of improved deterrence is biologically significant at the population level.

Table 6-20
Deterrence Efficiency Statistics for BAFF Operations in 2010

Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.150	0.012	13.8	13.095	0.0003
Standard Deviation	0.193	0.044			
Minimum	0.000	0.000			
Maximum	0.680	0.200			
Samples (n)	19	22			

Notes: BAFF = bio-acoustic fish fence; n = number of deterrence efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

The apparent D_E with the BAFF off was 1.2%. This is the percentage of juvenile Chinook salmon that exhibited movements that appeared to be movements away from the BAFF or guided along the line of the BAFF even though the BAFF was off.

The 2010 mean D_E with the BAFF on was 15.0% in the analysis reported in Table 6-20. This is slightly less than the grand D_E reported in Bowen et al. (2012), which was 23.0%. Similar to 2009, this difference arose from the reanalysis of the deterrence data in the present study, because fish were placed into samples from the same time period with similar values for ambient light and ACV when the fish arrived at the HOR study area (see definition of samples in Chapter 5, "Methods"), instead of being placed in groups that were associated with the release date/ time.

Effect of Ambient Light Level on BAFF Deterrence Efficiency

When the samples for 2010 BAFF D_E were partitioned by ambient light level (Table 6-21), 9 to 12 samples were found for various combinations of BAFF operations and light levels. For high-light levels, D_E with the BAFF on was 26.0 percentage points higher than with the BAFF off (Table 6-22), and this difference was statistically significant. However, there was no improvement in D_E with the BAFF on compared to off at low light levels. In 2010, similar to 2009, it appeared that light did influence the BAFF's D_E at light levels greater than or equal to 5.4 lux.

Table 6-21
Summary of Deterrence Efficiency Samples for Tagged Juvenile Chinook Salmon Encountering BAFF during On/Off Operations at Low and High Light Levels in 2010

Ambient Light Level	BAFF On (n)	BAFF Off (n)
Low Light (<5.4 lux)	9	12
High Light (≥5.4 lux)	10	10
Total	19	22

Notes: BAFF = bio-acoustic fish fence; n = number of deterrence efficiency samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-22
2010 BAFF Operations—Mean Deterrence Efficiency for Tagged Juvenile Chinook Salmon at Low and High Light Levels

Ambient Light Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Light (<5.4 lux)	0.019	0.017	0.2	0.575	0.4481
High Light (≥5.4 lux)	0.267	0.007	26.0	15.093	0.0001

Note: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Effect of Average Channel Velocity on Barrier Deterrence Efficiency

When the samples for 2010 D_E were partitioned by ACV level, only four samples were acquired for high-ACV conditions for both the BAFF on and BAFF off (Table 6-23). For low-ACV conditions, D_E with the BAFF on was 11.1 percentage points higher than off (Table 6-24). In addition, D_E with the BAFF on was 23.6 percentage points higher than off for high-ACV conditions (Table 6-24). In 2010, the BAFF improved D_E under both low- and high-ACV conditions.

Table 6-23
Summary of Deterrence Efficiency Samples for Tagged Juvenile Salmon Encountering BAFF during On/Off Operations at Low and High Average Channel Velocity Levels in 2010

Average Channel Velocity Level	BAFF On (n)	BAFF Off (n)
Low Velocity (<0.61 m/s)	15	18
High Velocity (≥0.61 m/s)	4	4
Total	19	22

Notes: BAFF = bio-acoustic fish fence; n = number of deterrence efficiency samples; m/s = meters per second
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-24 2010 BAFF Operations—Mean Deterrence Efficiency for Tagged Juvenile Chinook Salmon at Low and High Average Channel Velocity Levels					
Average Channel Velocity Level	BAFF On Mean	BAFF Off Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Velocity (<0.61 m/s)	0.122	0.011	11.1	8.562	0.0034
High Velocity (≥0.61 m/s)	0.254	0.018	23.6	5.600	0.0180

Note: BAFF = bio-acoustic fish fence; m/s = meters per second
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

6.1.3 2009 COMPARED TO 2010

STUDY FISH

There were three important differences in the juvenile Chinook salmon used in 2009 and 2010. The juvenile Chinook salmon used in 2009 were from the Feather River Hatchery and were fall-spring–run hybrids. Juvenile Chinook salmon used in 2010 were from the Merced River Hatchery and were fall-run (Table 5-1). Also, the range of sizes was different between the two years. The Feather River Hatchery fall-spring hybrid individuals were 80 to 110 mm TL while the Merced River Hatchery fall-run individuals were 99 to 121 mm TL. Finally, the tag burden was higher than 5.4% for a large proportion of juvenile Chinook salmon in 2009 over 2010 (Table 5-3).

In addition to differences in the juvenile Chinook salmon, there were differences in the BAFF location, orientation, length, and shape (Figure 4-3). The principal objective in comparing 2009 and 2010 was to determine which of these two shapes seemed to best improve P_E. However, the analysis was confounded by the three important differences between the juvenile Chinook salmon between the two years.

OVERALL EFFICIENCY

The number of samples ranged from 19 to 27 for BAFF operations in 2009 and 2010 (Table 6-25). There was not a statistical difference between 2009 and 2010 in any measured variable (Table 6-26); hypotheses $H3_0$ and $H4_0$ were accepted. With the BAFF on, O_E was never higher than 35.5%. Thus, it appeared the BAFF was not effective at maintaining juvenile Chinook salmon in the San Joaquin River. The 2010 O_E with the BAFF on showed a 14.6-percentage-point improvement over 2009; the P-value was 0.0563, but the statistical power was only 0.489. These results suggested that there could be differences between 2009 and 2010 BAFF alignments, but low power meant it was not possible to reject a false null hypothesis (Table 1-1: $H3_0$).

Table 6-25 Overall Efficiency Samples with BAFF Operations—2009 vs. 2010			
Treatment	2009 (n)	2010 (n)	Total
BAFF On	21	19	40
BAFF Off	27	22	49
BAFF Effect	15	11	26

Notes: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-26 Overall Efficiency Statistics with BAFF Operations—2009 vs. 2010					
Treatment	2009 Mean	2010 Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
BAFF On	0.209	0.355	-14.6	3.645	0.0563
BAFF Off	0.184	0.245	-6.1	1.958	0.1617
BAFF Effect	0.047	0.080	-3.3	0.017	0.8967

Note: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

PROTECTION EFFICIENCY

The number of P_E samples ranged from 18 to 25 in 2009 and 2010 (Table 6-27). There were fewer BAFF effect samples, 11 to 12. Calculation of BAFF effect required a switch in BAFF status while ACV and light level were consistent. That did not happen on every BAFF switch occasion. No statistical difference was observed between 2009 and 2010 in any measured variable (Table 6-28); P_E with the BAFF on was never higher than 44.1%. Hypotheses $H3_0$ and $H4_0$ were accepted. Thus, it appeared the BAFF was not effective under any conditions studied, thus it did not facilitate maintaining juvenile Chinook salmon in the San Joaquin River.

Table 6-27 Protection Efficiency Samples with BAFF Operations—2009 vs. 2010			
Treatment	2009 (n)	2010 (n)	Total
BAFF On	18	25	43
BAFF Off	19	20	39
BAFF Effect	12	11	33

Notes: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-28 Protection Efficiency Statistics with BAFF Operations—2009 vs. 2010					
Treatment	2009 Mean	2010 Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
BAFF On	0.338	0.441	-10.4	1.567	0.2106
BAFF Off	0.234	0.286	-5.2	0.635	0.4256
BAFF Effect	0.108	0.145	-3.7	0.077	0.7817

Note: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

DETERRENCE EFFICIENCY

The number of D_E samples ranged from 18 to 23 in 2009 and 2010 (Table 6-29). In 2009, operation of the BAFF produced much greater D_E than in 2010 (a 58.2-percentage-point improvement). However, with the BAFF off, there was also a 29.9-percentage-point greater D_E in 2009 than in 2010 (Table 6-30). The percentage of juvenile Chinook salmon that appeared deterred with the BAFF off was 31.1% in 2009 and 1.2% in 2010, and were different (see Table 6-30). Hypotheses $H3_0$ and $H4_0$ were rejected.

Table 6-29
Deterrence Efficiency Samples with BAFF Operations—2009 vs. 2010

Treatment	2009 (n)	2010 (n)	Total
BAFF On	18	19	37
BAFF Off	23	22	45
BAFF Effect	10	11	21

Notes: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-30
Deterrence Efficiency Statistics with BAFF Operations—2009 vs. 2010

Treatment	2009 Mean	2010 Mean	Percentage Point Change	Kruskal-Wallis X^2	P-Value
BAFF On	0.732	0.150	58.2	16.997	<0.0001
BAFF Off	0.311	0.012	29.9	18.351	<0.0001
BAFF Effect	0.432	0.166	26.6	3.248	0.0715

Notes: BAFF = bio-acoustic fish fence
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

In 2009, the calculated BAFF effect on D_E was 26.6 percentage points greater than in 2010. Thus, the difference in calculated D_E due to the BAFF effect from 2009 to 2010 accurately approximated the difference in D_E from 2009 to 2010, due only to BAFF operation rather than other factors. Although it appeared that BAFF operation resulted in much greater deterrence in 2009, the deterrence due to the BAFF effect was not different from 2009 to 2010, possibly due to sample sizes of 10 and 11 (Table 6-29), and relatively low statistical power (0.444).

6.1.4 2011 RESULTS

SIZE AND SOURCE OF JUVENILE CHINOOK SALMON AND STEELHEAD USED

The juvenile Chinook salmon tagged and released in 2011 were similar in size to those in 2010 and 2012 and larger than 2009 (Table 5-1).

The juvenile steelhead implanted with tags and released in 2011 were larger than the tagged juvenile Chinook salmon (Table 5-1). In 2011, the Mokelumne River Fish Hatchery provided the juvenile steelhead used in the studies; the production of the juvenile steelhead is described in Section B.1 of Appendix B.

CHINOOK SALMON OVERALL AND PROTECTION EFFICIENCY STATISTICS

In 2011, there were 53 samples of tagged juvenile Chinook salmon for which O_E and P_E could be calculated (Table 6-31). With no barrier installed, 51.9% of tags in juvenile Chinook salmon continued down the San Joaquin River. However, when the juvenile Chinook salmon that had been determined to be eaten were removed, the P_E improved. With no barrier installed, 57.4% of the juvenile Chinook salmon determined to have not been consumed went down the San Joaquin River. The mean proportion of flow into the San Joaquin River during the period of fish release was 48% (Table 3-1). In 2009 and 2010 the proportion of juvenile Chinook salmon entering the San Joaquin River was lower than the proportion of flow. In contrast in 2011, the proportion of juvenile Chinook salmon entering the San Joaquin River was similar to the proportion of flow.

Table 6-31
Chinook Salmon Statistics for the No-Barrier Treatment in 2011

	Mean	Standard Deviation	Minimum	Maximum	Number of Samples (n)
Overall Efficiency	0.519	0.160	0.000	1.000	53
Protection Efficiency	0.574	0.178	0.000	1.000	53

Notes: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

6.1.5 2009 BAFF OFF COMPARED TO 2010 BAFF OFF COMPARED TO 2011

OVERALL EFFICIENCY— JUVENILE CHINOOK SALMON

O_E was significantly different between treatments at the HOR study area with the BAFF off in 2009 and 2010, and with no barrier in 2011 (Kruskal-Wallis $X^2 = 49.008$, P-value <0.0001). Hypothesis $H5_0$ was rejected. There was no significant difference in O_E in 2009 with the BAFF off compared to 2010 with the BAFF off (Table 6-26). Thus, 2009 with the BAFF off was grouped with 2010 with the BAFF off (Table 6-32). Because the data did not meet the assumptions of ANOVA, one nonparametric two-sample comparison was made between treatments (i.e., 2010 vs. 2011). The O_E in 2011 was significantly greater than O_E in 2010 with the BAFF off (Kruskal-Wallis $X^2 = 26.577$, P-value <0.0001).

Table 6-32
Statistics for Overall Efficiency for 2009–2011

Treatment—Year	Mean	Standard Deviation	Number of Samples (n)	Statistical Grouping
BAFF Off—2009	0.184	0.185	27	a
BAFF Off—2010	0.245	0.183	22	a
No Barrier—2011	0.519	0.160	53	b

Note: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

PROTECTION EFFICIENCY—JUVENILE CHINOOK SALMON

P_E was significantly different for the BAFF-off and "no barrier" years at the HOR study area (Kruskal-Wallis $X^2 = 39.650$, P-value <0.0001). Hypothesis $H5_0$ was rejected. There was no significant difference in P_E with the BAFF off in 2009 compared to 2010 (Table 6-28); so, the "BAFF Off—2009" statistics were grouped with the "BAFF Off—2010" statistics (Table 6-33). Because the data did not meet the assumptions of ANOVA, one nonparametric two-sample comparison was made between treatments (i.e., 2010 vs. 2011). The P_E in 2011 was greater than the P_E with the BAFF off for 2009 and 2010 (Kruskal-Wallis $X^2 = 21.378$, P-value <0.0001).

Table 6-33
Statistics for Protection Efficiency for 2009–2011

Treatment—Year	Mean	Standard Deviation	Number of Samples (n)	Statistical Grouping
BAFF Off—2009	0.234	0.220	25	a
BAFF Off—2010	0.286	0.206	20	a
No Barrier—2011	0.574	0.178	53	b

Note: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM.

6.1.6 2011 JUVENILE CHINOOK SALMON COMPARED TO JUVENILE STEELHEAD

OVERALL EFFICIENCY

The number of O_E samples ranged from 53 to 93 for juvenile Chinook salmon and juvenile steelhead (Table 6-34). The O_E for tagged juvenile Chinook salmon that passed the San Joaquin River finish line was 51.9% (Table 6-34).

Table 6-34
Statistics for Overall Efficiency for Tagged Juvenile Chinook Salmon and Steelhead in 2011

Statistic	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^2	P-value
Mean of Samples	0.519	0.368	15.1	12.717	0.0004
Standard Deviation	0.160	0.287			
Minimum	0.000	0.000			
Maximum	1.000	1.000			
Samples (n)	53	93			

Note: n = number of samples
Overall Efficiency reported in this table is the mean of samples. The grand overall efficiency (see text) was 38.3%.
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

For juvenile steelhead, the O_E was significantly lower (Kruskal-Wallis $X^2 = 12.717$, P = 0.0004) than for juvenile Chinook salmon (Table 6-34). Hypothesis $H6_0$ was rejected. However, in 2011, 37.7% of steelhead selected the Old River route and this was similar to the usage of the Old River route by Chinook (38.6%). Recall that O_E includes all tags (even those originally in juvenile salmonids that were eaten and now in predators) that pass by

the finish lines. This largely appeared to reflect greater predation on juvenile steelhead (see section 6.2.1, "Proportion Eaten (Univariate Analyses)").

The mean of overall efficiency samples was 36.8% (Table 6-34). This mean was calculated as the mean of all the samples derived by the method described in Methods (Section 5.2.1 "Grouping Juvenile Salmonids Iinto Samples"). The grand overall efficiency was 38.3%. The grand mean overall efficiency was calculated as the total number of tags, originally inserted into steelhead, that remained in the San Joaquin River (199) divided by the total number tags (520) that moved past the Head of Old River study site. This difference between these values arose from how the tags were allocated into samples but the difference was very small between the two measures.

Tagged juvenile Chinook salmon and steelhead passed through the HOR study area at various light levels (Figure 6-5). When the 2011 juvenile salmonids were placed into samples, and the O_E samples were partitioned by light level, 25 to 61 samples were distributed throughout the experimental matrix (Table 6-35). Also, tagged juvenile Chinook salmon and steelhead passed through the HOR study area at various ACV levels (Figure 6-6). When the 2011 juvenile salmonids were placed into samples and the O_E samples were partitioned by ACV level, sample sizes ranged from 24 to 48 (Table 6-37). The relationships (discussed in Section 6.1.6, "Overall Efficiency") for juvenile Chinook salmon and steelhead O_E were similar for all light and ACV levels. That is, juvenile Chinook salmon had an approximate 15-percentage-point greater O_E than did steelhead for all light levels and ACV levels (Tables 6-34, 6-36, and 6-38), and this difference was significant. It was concluded that, at both light levels and at both ACV levels studied, tagged juvenile Chinook salmon had an approximately 15% greater chance of following the San Joaquin River route compared to tagged steelhead.

Table 6-35
Summary of Overall Efficiency Samples for Tagged Chinook Salmon and Steelhead at Low and High Ambient Light Levels in 2011

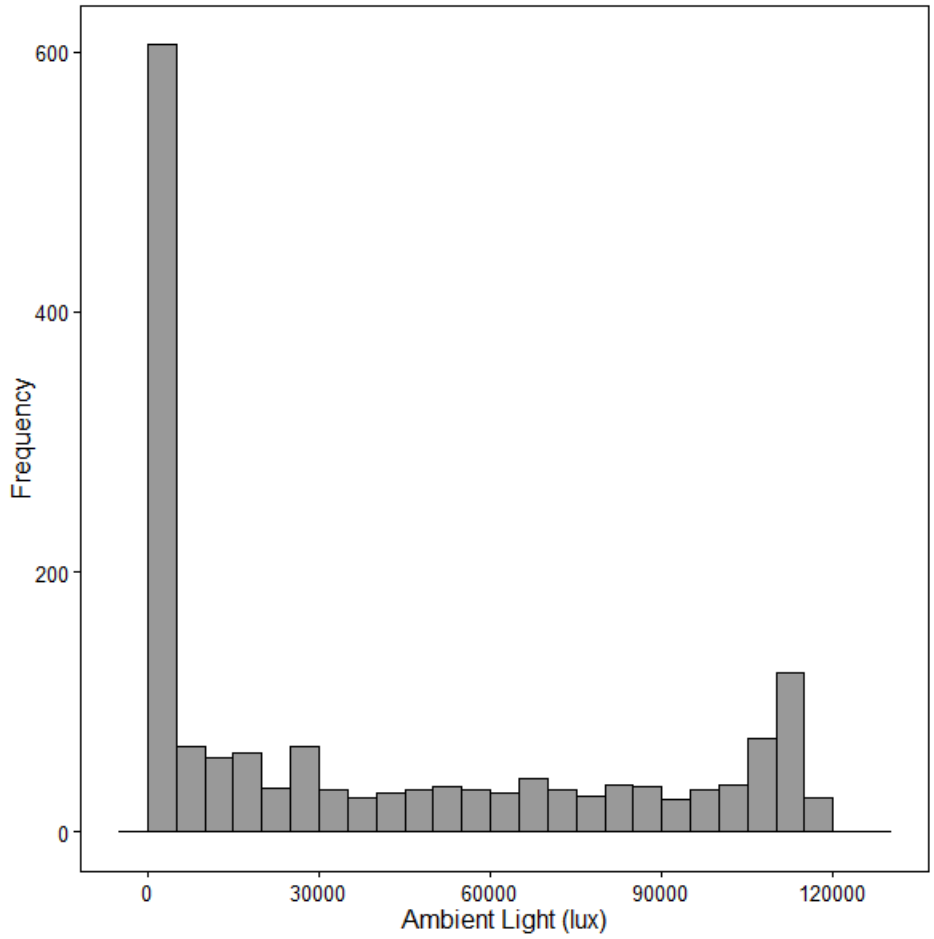
Ambient Light Level	Chinook Salmon (n)	Steelhead (n)	Total (n)
Low Light (<5.4 lux)	25	32	57
High Light (≥5.4 lux)	28	61	89

Note: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-36
Mean Overall Efficiency for Tagged Juvenile Chinook Salmon and Steelhead at Low and High Light Levels in 2011

Ambient Light Level	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Light (<5.4 lux)	0.540	0.367	17.3	5.426	0.0198
High Light (≥5.4 lux)	0.501	0.368	13.3	6.854	0.0088

Source: Data compiled by Turnpenny Horsfield Associates and AECOM



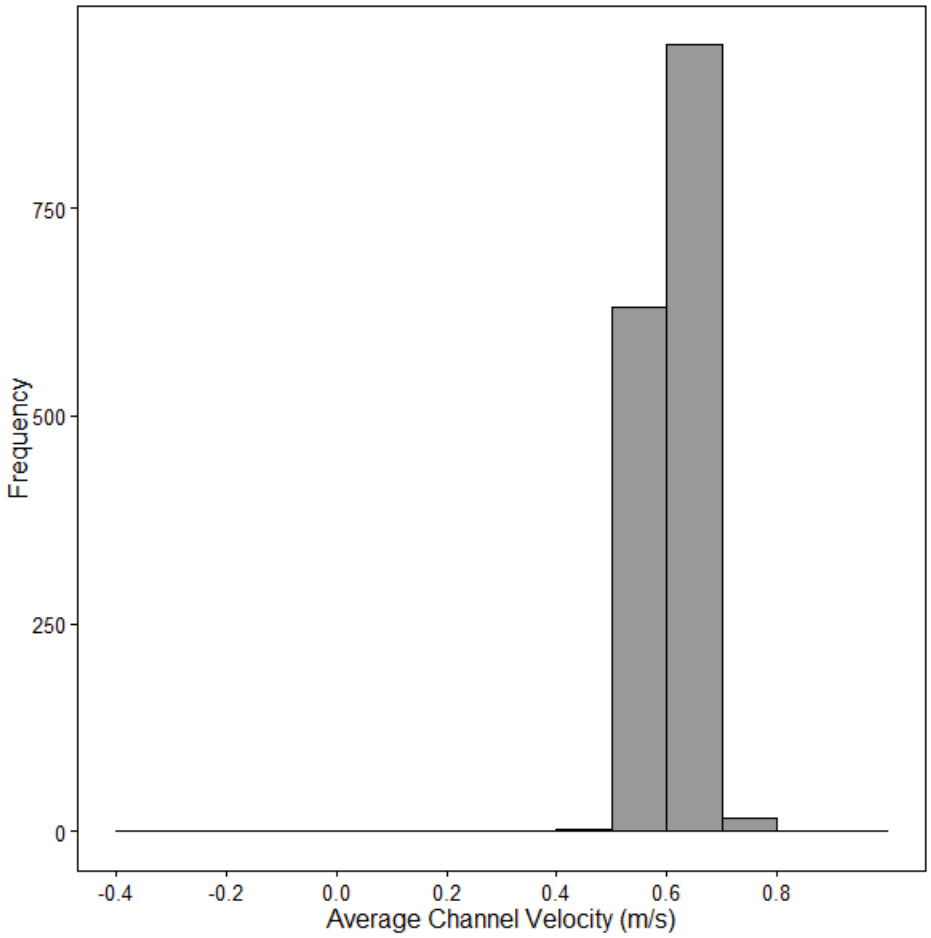
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Figure 6-5 Frequency Histogram of 2011 Light-Level Observations (collected at CIMIS, Station #70–Manteca, 37.834822, -121.223194) Obtained for Each Tagged Juvenile Salmonid when the Individual was Nearest the 2010 BAFF Line

Table 6-37
Summary of Overall Efficiency Samples for Tagged Juvenile Chinook Salmon and Steelhead at Low and High Average Channel Velocity Levels in 2011

Average Channel Velocity Level	Chinook Salmon (n)	Steelhead (n)	Total (n)
Low Velocity (<0.61 m/s)	29	48	77
High Velocity (≥0.61 m/s)	24	45	69
Total	53	93	146

Note: n = number of samples; m/s = meters per second
Source: Data compiled by Turnpenny Horsfield Associates and AECOM



Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Figure 6-6 **Frequency Histogram of 2011 Average Channel Velocity Observations (SJL Gauge) Obtained for Each Tagged Juvenile Salmonid when the Individual was Nearest the 2010 BAFF Line**

Table 6-38
Mean Overall Efficiency for Tagged Juvenile Chinook Salmon and Steelhead at Low and High Average Channel Velocity Levels in 2011

Average Channel Velocity Level	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Velocity (<0.61 m/s)	0.489	0.341	14.8	6.793	0.0092
High Velocity (≥0.61 m/s)	0.555	0.396	15.9	7.063	0.0079

Note: m/s = meters per second
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

PROTECTION EFFICIENCY

The difference observed in O_E for juvenile Chinook salmon compared to steelhead was not observed in P_E (Table 6-39). It was notable that the P_E for steelhead, 49.0%, was consistent with the proportion of flow into the San Joaquin River, 48% (Table 3-1), but the P_E for juvenile Chinook salmon, 57.4%, was higher; the difference was not significant. Hypothesis $H6_0$ was accepted.

Table 6-39
Statistics for Protection Efficiency for Tagged Juvenile Chinook Salmon and Steelhead in 2011

Statistic	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.574	0.490	8.4	2.511	0.1131
Standard Deviation	0.178	0.296			
Minimum	0.000	0.000			
Maximum	1.000	1.000			
Samples (n)	53	77			

Note: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

The sample-size tables for ambient light level and ACV (Tables 6-40 and 6-42) show greater than 20 samples for every combination of species, light level, and ACV. There were no differences in P_E between juvenile Chinook salmon and steelhead for any light level or ACV level (Tables 6-41 and 6-43).

Table 6-40
Summary of Protection Efficiency Samples for Tagged Juvenile Chinook Salmon and Steelhead at Low and High Ambient Light Levels in 2011

Ambient Light Level	Chinook Salmon (n)	Steelhead (n)	Total (n)
Low Light (<5.4 lux)	25	26	51
High Light (≥5.4 lux)	28	51	79

Note: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-41
Mean Protection Efficiency for Tagged Juvenile Chinook Salmon and Steelhead at Low and High Ambient Light Levels in 2011

Ambient Light Level	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Light (<5.4 lux)	0.565	0.440	12.5	1.786	0.1814
High Light (≥5.4 lux)	0.581	0.516	6.5	1.112	0.2916

Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-42
Summary of Protection Efficiency Samples for Tagged Juvenile Chinook Salmon and Steelhead at Low and High Average Channel Velocity Levels in 2011

Average Channel Velocity Level	Chinook Salmon (n)	Steelhead (n)	Total (n)
Low Velocity (<0.61 m/s)	29	38	67
High Velocity (≥0.61 m/s)	24	39	63

Note: n = number of samples; m/s = meters per second
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Table 6-43
Mean Protection Efficiency for Tagged Juvenile Chinook Salmon and Steelhead at Low and High Average Channel Velocity Levels in 2011

Average Channel Velocity Level	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Low Velocity (<0.61 meter per second)	0.545	0.473	7.2	1.384	0.2395
High Velocity (≥0.61 meter per second)	0.608	0.508	10.0	1.459	0.2271

Source: Data compiled by Turnpenny Horsfield Associates and AECOM

6.1.7 2012 RESULTS

SIZE AND SOURCE OF JUVENILE CHINOOK SALMON AND STEELHEAD USED

The juvenile Chinook salmon tagged and released in 2012 were similar in size to those released in 2010 and 2011 and came from the Merced River Hatchery (Table 5-1). Similar to 2011, the tagged juvenile steelhead released in 2012 were larger than the tagged juvenile Chinook salmon (Table 5-1). In 2012, the Mokelumne River Hatchery was the source of juvenile steelhead.

PHYSICAL BARRIER OVERALL AND PROTECTION EFFICIENCY—CHINOOK SALMON

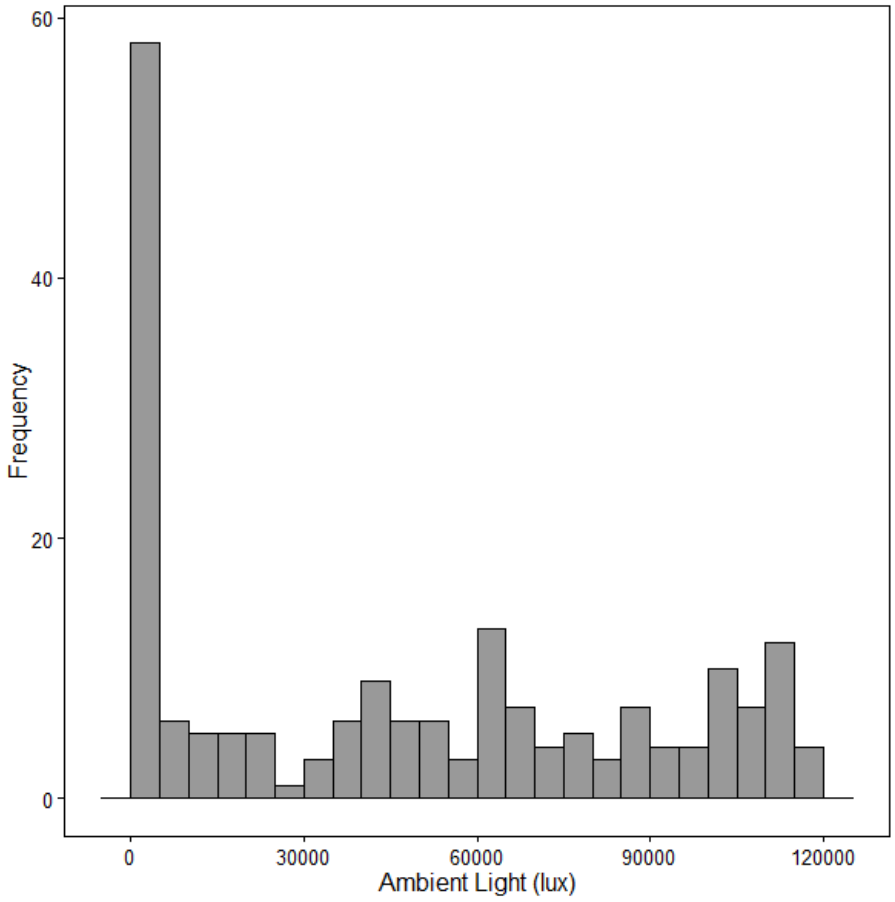
In 2012, there were 21 to 27 samples of tagged juvenile Chinook salmon for which O_E and P_E could be calculated (Table 6-44).[1] The number of samples available for P_E was always less than or equal to the number of samples of O_E because, for some samples, enough juvenile Chinook salmon were eaten to remove the samples from P_E consideration due to insufficient sample size (n <2). With a physical rock barrier installed, 61.8% of tagged juvenile Chinook salmon continued down the San Joaquin River. In contrast, 100% of tagged juvenile Chinook salmon that were not eaten continued down the San Joaquin River. In addition, the mean proportion of flow into the San Joaquin River during the study period was 82% (Table 3-1). Thus, the proportion of juvenile Chinook salmon remaining in the San Joaquin River was higher than the proportion of flow.

[1] Note: The BAFF 2010 line was used in 2010, 2011, and 2012 for a consistent reference line across years.

Table 6-44 Physical Rock Barrier Statistics for Tagged Juvenile Chinook Salmon in 2012					
Efficiency Type	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**	**Number of Samples (n)**
O_E	0.618	0.321	0.000	1.000	27
P_E	1.000	0.000	1.000	1.000	21

Note: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Tagged juvenile Chinook salmon passed through the HOR study area at various ambient light levels (Figure 6-7). When the 2012 juvenile Chinook salmon were placed into samples and the O_E samples were partitioned by light level, 11 to 16 samples were found (Table 6-45). Tagged juvenile Chinook salmon passed through the HOR study area at various ACV levels (Figure 6-8). When the 2012 juvenile Chinook salmon were placed into samples, no samples were obtained at ACVs greater than 0.61 m/s.



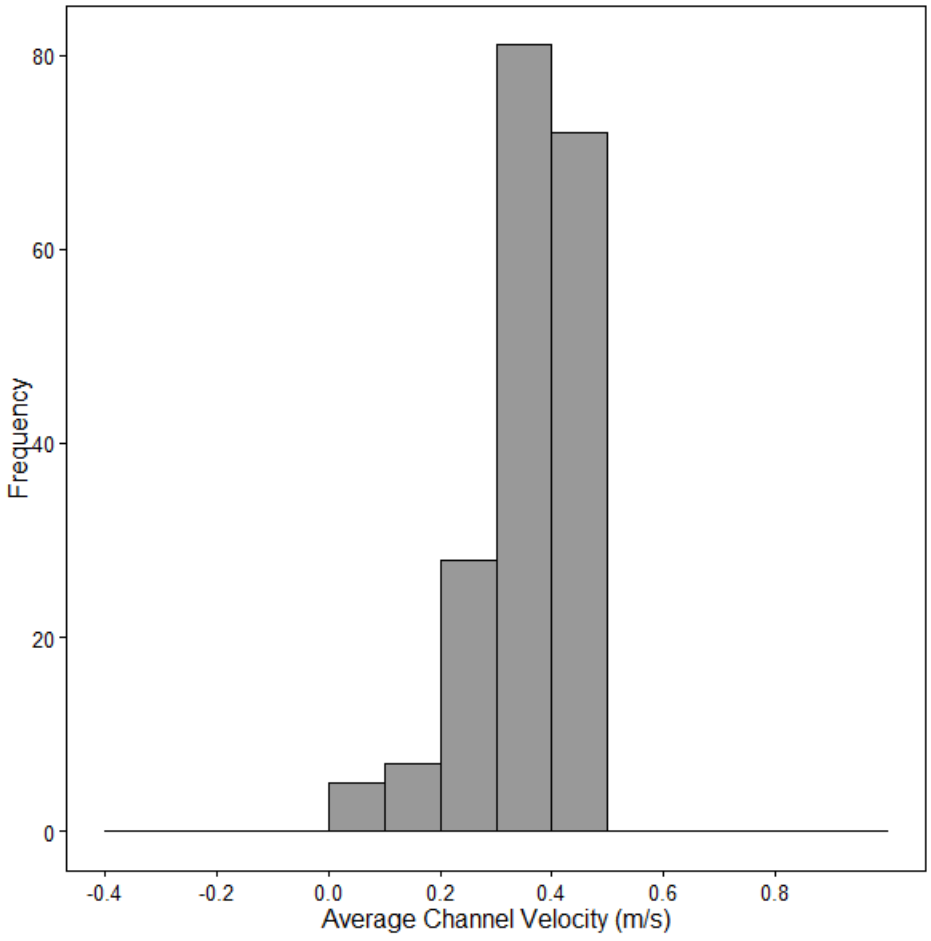
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Figure 6-7 Frequency Histogram of 2012 Light-Level Observations (collected at CIMIS, Station #70–Manteca, 37.834822, -121.223194) Obtained for Each Tagged Juvenile Chinook Salmon when the Individual was Nearest the 2010 BAFF Line

Table 6-45
Statistics for Overall Efficiency for Tagged Juvenile Chinook Salmon at Low and High Ambient Light Levels in 2012

Statistic	Low Ambient Light (<5.4 lux)	High Ambient Light (≥5.4 lux)	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.868	0.446	42.2	12.204	0.0005
Standard Deviation	0.203	0.271			
Minimum	0.500	0.000			
Maximum	1.000	0.842			
Samples (n)	11	16			

Note: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM



Source: Data compiled by Turnpenny Horsfield Associates and AECOM

Figure 6-8 **Frequency Histogram of 2012 Average Channel Velocity Observations (SJL Gauge) Obtained for Each Tagged Juvenile Chinook Salmon when the Individual was Nearest the 2010 BAFF Line**

In 2012, the mean O_E for tagged juvenile Chinook salmon was 42.2 percentage points greater for tagged juvenile Chinook salmon encountering the rock barrier in low-light levels than for tagged juvenile Chinook salmon encountering the barrier in high-light levels (Table 6-45). This difference was statistically significant, and may have been a result of higher predation rates at high-light levels, a feature that was apparent from GLM of juvenile Chinook salmon for 2009 through 2012 data (see Section 6.2.2). This is explored further under in Section 6.2.1, "Proportion Eaten (Univariate Analyses)."

When tags implanted in juvenile Chinook salmon and subsequently determined to have been eaten by predators were removed from consideration, the physical rock barrier's P_E was 100% efficient for both low- and high-light levels. In addition, P_E was not different for juvenile Chinook salmon that encountered the rock barrier at different light levels (Table 6-46). This result supports the hypothesis that the large difference in O_E under varying light levels (Table 6-45) was due to greater predation on juvenile Chinook salmon during the day. As noted previously, this topic is explored further under in Section 6.2.1, "Proportion Eaten (Univariate Analyses)."

Table 6-46
Statistics for Protection Efficiency for Tagged Juvenile Chinook Salmon at Low and High Ambient Light Levels in 2012

Statistic	Low Ambient Light (<5.4 lux)	High Ambient Light (≥5.4 lux)	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	1.000	1.000	0.0	NA	NA
Standard Deviation	0.000	0.000			
Minimum	1.000	1.000			
Maximum	1.000	1.000			
Samples (n)	10	11			

Note: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

OVERALL AND PROTECTION EFFICIENCY—STEELHEAD

Of the five tagged steelhead that arrived at the HOR study area in 2012, one was eaten in the study area and four went down the San Joaquin River. Thus, the grand O_E for steelhead in 2012 was 0.800, and the grand P_E was 1.000.

6.1.8 COMPARISON AMONG CONDITIONS FROM 2009 (BAFF ON), 2010 (BAFF ON), 2011 (NO BARRIER), AND 2012 (PHYSICAL ROCK BARRIER)

OVERALL EFFICIENCY—CHINOOK SALMON

O_E was significantly different between barrier treatments at the HOR study area (Kruskal-Wallis $X^2 = 34.311$, P-value <0.0001). Hypothesis $H7_0$ was rejected. The BAFF showed no difference in O_E in 2009 compared to 2010 (Table 6-26); therefore, the 2009 "BAFF On" statistics were grouped with the 2010 "BAFF On" statistics (Table 6-47). Because the data did not meet the assumptions of ANOVA, three nonparametric two-sample comparisons were made between treatments: 2010 compared to 2011; 2010 compared to 2012; and 2011 compared to 2012.

To make multiple two-sample comparisons, a Bonferroni-method reduction of the critical alpha was employed to control the experiment-wise error rate: 0.05/3 = 0.0167 (Sokal and Rohlf 1995). The only two-sample comparison that was not among these three tests was 2011 compared to 2012 (Kruskal-Wallis $X^2 = 2.759$, P-value = 0.0967). The statistical power of this last test was 0.885, which exceeds the conventional value of 0.80 (Cohen 1988). Thus, it was concluded that there is likely no true difference between O_E of 2011 compared to 2012.

It was concluded that the BAFF produced the lowest O_E among the three treatment types. There was no difference in "no barrier" O_E and "physical rock barrier" O_E.

Table 6-47
Statistics for Overall Efficiency from 2009–2012

Treatment—Year	Mean	Standard Deviation	Number of Samples (n)	Statistical Grouping
BAFF On—2009	0.209	0.218	21	a
BAFF On—2010	0.355	0.243	19	a
No Barrier—2011	0.519	0.160	53	b
Rock Barrier—2012	0.618	0.321	27	b

Note: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

PROTECTION EFFICIENCY—CHINOOK SALMON

P_E was significantly different between barrier treatments at the HOR study area (Kruskal-Wallis $X^2 = 49.630$, P-value <0.0001). Hypothesis $H7_0$ was rejected. The BAFF showed no significant difference in P_E in 2009 compared to 2010 (Table 6-28); therefore, the 2009 "BAFF On" statistics were grouped with the 2010 "BAFF On" statistics (Table 6-48). Because the data did not meet the assumptions of ANOVA, three nonparametric two-sample comparisons were made between treatments (i.e., 2010 compared to 2011; 2010 compared to 2012; and 2011 compared to 2012). As noted above, the critical alpha for these comparisons was 0.0167. The 2010 and 2011 data met the assumptions of ANOVA, and the pairwise comparison used this traditional parametric statistical approach (F = 6.413, P-value = 0.0136).

Table 6-48
Statistics for Protection Efficiency from 2009–2012

Treatment—Year	Mean	Standard Deviation	Number of Samples (n)	Statistical Grouping
BAFF On—2009	0.338	0.330	18	a
BAFF On—2010	0.441	0.239	19	a
No Barrier—2011	0.574	0.178	53	b
Rock Barrier—2012	1.000	0.000	21	c

Note: BAFF = bio-acoustic fish fence; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM

It was concluded that the BAFFs in 2009 and 2010 grouped together had the lowest P_E among the three treatment types (Table 6-48). However, once eaten tags were removed, leaving only surviving tags-in-Chinook-salmon, there was considerable improvement in P_E compared to O_E (compare Tables 6-47 and 6-48). In contrast to the O_E results, there was a difference in "no barrier" P_E and "physical rock barrier" P_E. The rock barrier P_E for surviving tags-in-Chinook-salmon was 100%. The mean proportion of flow passing through the culverts was 18% (Table 3-1), which was higher than the percentage of juvenile Chinook salmon passing down Old River. Note that two juvenile Chinook salmon were actually detected passing through the culverts, but these were subsequently preyed upon in the HOR study area downstream of the rock barrier, so their fate was not recorded as "Old River" but as "Predation."

6.2 PREDATION ON JUVENILE SALMONIDS INCLUDING BARRIER EFFECTS

6.2.1 PROPORTION EATEN (UNIVARIATE ANALYSES)

2009 RESULTS

In 2009, the proportion of juvenile Chinook salmon determined to have been eaten with the BAFF on and off combined was 22.9% in the HOR study area. Thus, the percentage uneaten was 77.1%; this value was similar to that reported for 2009 survival in the Mossdale-to-HOR reach, 83.0%, by SJRGA (2010). The proportion eaten was 15.2% higher with the BAFF on than with the BAFF off, and this difference was significant (Table 6-49). Hypothesis $H8_0$ was rejected. These results suggested that the BAFF caused an increase in predation when it was operated in 2009.

Table 6-49
Proportion of Juvenile Chinook Eaten Statistics for BAFF Operations in 2009

Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^{2a}	P-Value[a]
Mean Sample Proportion Eaten[a]	0.290	0.138	15.2	5.391	0.0202
Standard Deviation[a]	0.216	0.167			
Samples (n)[a]	21	27			
Population Proportion Eaten[b]	0.309	0.164	14.5		
Standard Error[b]	0.030	0.022			

Notes: BAFF = bio-acoustic fish fence; n = number of samples
[a] Sample proportion eaten parameters
[b] Population proportion eaten parameters
Source: Present study

2010 RESULTS

The proportion of juvenile Chinook salmon eaten with the BAFF on and off combined was 25.9% in the HOR study area. Because the proportion eaten reported in 2009 was 22.9%, it appeared that in both years the BAFF was studied (2009 and 2010), the predation rate was consistent. In contrast to 2009, in 2010, the proportion eaten was 0.5 percentage point higher with the BAFF on than off; this difference was not statistically significant (Table 6-50). Hypothesis $H8_0$ was accepted. It is not known why this difference occurred in 2009 but not in 2010.

Table 6-50
Proportion of Juvenile Chinook Eaten Statistics for BAFF Operations in 2010

Statistic	BAFF On	BAFF Off	Percentage Point Change	Kruskal-Wallis X^2[b]	P-Value[b]
Mean Sample Proportion Eaten[a]	0.217	0.212	0.5	0.051	0.8218
Standard Deviation[a]	0.217	0.167			
Samples (n)[a]	19	22			
Population Proportion Eaten[b]	0.310	0.205			
Standard Error[b]	0.030	0.027			

Notes: BAFF = bio-acoustic fish fence; n = number of samples
[a] Sample proportion eaten parameters
[b] Population proportion eaten parameters
Source: Present study

The major differences between the two years were the lower mean turbidities and lower discharge magnitudes in 2009. These results suggest an area of interesting future inquiry. It was notable that, for 2010, the sample proportion eaten with the BAFF on, 0.217, was lower than the population proportion eaten, 0.310. This difference was a result of how the tags were sorted into samples: Of the 19 samples in question, seven samples, each containing two to 11 tags, had a proportion eaten of zero. In contrast, the remaining 12 samples ranged in size from six to 28 tags, with an average proportion eaten of 0.344, which was consistent with the population proportion eaten.

2009 COMPARED TO 2010

The number of proportion eaten samples ranged from 19 to 27 in 2009 and 2010 (Table 6-51). In 2009, the ratio of proportion eaten with the BAFF on compared to the BAFF off was 1.88, and that was similar to the ratio in 2010 (1.51), suggesting similar predation pressure between years. In 2009, the proportion of tags eaten was not statistically different from the proportion eaten in 2010 (Table 6-52) for the BAFF on or off. However, the statistical power of the test for the BAFF off was only 0.426, and the P-value for the comparison between 2009 and 2010 with the BAFF off was 0.0749. Thus, it is possible that there was a difference in the "BAFF off" proportion eaten in 2009 compared to 2010, and low power made it difficult to resolve.

Table 6-51
Proportion of Juvenile Chinook Eaten Samples with BAFF Operations—2009 vs. 2010

Treatment	2009 (n)	2010 (n)	Total (n)
BAFF On	21	19	40
BAFF Off	27	22	49

Notes: BAFF = bio-acoustic fish fence; n = number of samples
Source: Present study

Table 6-52
Proportion of Juvenile Chinook Eaten Statistics with BAFF Operations—2009 vs. 2010

Sample Proportion Eaten					
Treatment	**2009 Mean Proportion Eaten[a]**	**2010, Mean Proportion Eaten[a]**	**Percentage Point Change**	**Kruskal-Wallis X^2[a]**	**P-value[a]**
BAFF On	0.290	0.217	7.3	1.530	0.2161
BAFF Off	0.138	0.212	-7.4	3.173	0.0749
Population Proportion Eaten					
Treatment	**2009 Proportion Eaten[b]**	**2010 Proportion Eaten[b]**	**Percentage Point Change**		
BAFF On	0.309	0.310	-0.1		
BAFF Off	0.164	0.205	-4.1		
Ratio On/Off	1.88	1.51			

Notes: BAFF = bio-acoustic fish fence

[a] Sample proportion eaten parameters are those derived from the proportion eaten of each group of fish that arrived at the HOR study area forming a single sample (see Section 5.2.1 in Chapter 5, "Methods," for the definition of a sample).

[b] Population proportion eaten parameters are those derived from the grand total eaten divided by the total number of tags in juvenile Chinook salmon (see definition in Section 5.3.1 in Chapter 5, "Methods").

Source: Present study

Another method to evaluate predation on juvenile Chinook salmon was to pool the proportion eaten with the BAFF on for 2009 and 2010. Then, the proportion eaten observations for the BAFF off were pooled for 2009 and 2010. There was no difference between the BAFF on proportion eaten (mean = 0.256) and the BAFF-off proportion eaten (mean = 0.171) when the years were pooled (Kruskal Wallis $X^2 = 3.043$, P = 0.0811); however, the statistical power of the test was low (0.427). It was concluded that it might not have been possible to resolve a true difference, given the sample size and power achieved.

COMPARISON OF 2009 BAFF OFF, 2010 BAFF OFF, AND 2011 CONDITIONS

In Table 6-53, the proportion of tags eaten was not significantly different between "BAFF Off—2009" and "No Barrier—2011" at the HOR study area (Kruskal-Wallis $X^2 = 0.523$, P-value = 0.4694). Additionally, the proportion of tags eaten was not significantly different between "BAFF Off—2009" and "BAFF Off—2010" (Table 6-52). The proportion of tags eaten was significantly different between "BAFF Off—2010" and "No Barrier—2011" at the HOR study area (Kruskal-Wallis $X^2 = 10.989$, P-value = 0.0009). The "No Barrier—2011" treatment produced the lowest predation level among all years studied at 0.101.

This may have been related to high discharge in 2011, resulting in several potential changes in the environment: (1) higher channel velocities that increased the salmonid juvenile transit rates (see Appendix D, "Transit Speed Analyses," Table D-13); (2) increased stage height that caused the predators to search a larger volume of water; (3) greater energetic cost for predators to swim in the thalweg than in other years, potentially reducing searched volume; (4) lower habitat suitability and fewer predators inhabiting the area; and/or (5) greater turbidity and, therefore, less ability for predators to see prey. Factors influencing predation rate are analyzed further in Section 6.2.2, "Probability of Predation (Generalized Linear Modeling)."

Table 6-53
Statistics for Proportion of Juvenile Chinook Eaten, 2009, 2010, and 2011

Sample Proportion Eaten				
Treatment—Year	**Proportion Eaten[1]**	**Standard Deviation[1]**	**Number of Samples (n)[1]**	**Statistical Grouping[2]**
BAFF Off—2009	0.138	0.167	27	ab
BAFF Off—2010	0.212	0.167	22	a
No Barrier—2011	0.087	0.091	53	b
Population Proportion Eaten				
Treatment—Year	**Proportion Eaten[2]**	**Standard Error[2]**		
BAFF Off—2009	0.164	0.022		
BAFF Off—2010	0.205	0.027		
No Barrier—2011	0.101	0.009		

Notes: BAFF = bio-acoustic fish fence

[1] Sample proportion eaten parameters are those derived from the proportion eaten of each group of fish that arrived at the HOR study area forming a single sample (see Section 5.2.1 in Chapter 5, "Methods," for the definition of a sample).

[2] Population proportion eaten parameters are those derived from the grand total eaten divided by the total number of tags in juvenile Chinook salmon (see definition in Section 5.3.1 in Chapter 5, "Methods").

Source: Present study

2011 CHINOOK SALMON COMPARED TO STEELHEAD

For 2011, the proportion of juvenile Chinook salmon determined to have been eaten was 0.087, and the proportion of juvenile steelhead determined to have been eaten was 0.243; this difference was significant (Table 6-54). Hypothesis $H9_0$ was rejected. However, there were two important related concepts: (1) there was a greater likelihood of steelhead being incorrectly assigned a fate of "eaten" compared to juvenile Chinook salmon (see the subsection entitled "Chinook Salmon Compared to Steelhead" in Section 7.1.4, "2011 No Barrier", of Chapter 7, "Discussion"); and (2) the juvenile steelhead used in this study were much larger than juvenile Chinook salmon (see Table 5-1 in Chapter 5, "Methods") and, therefore, probably had better swimming capabilities.

There were major differences in the behavior pattern of juvenile Chinook salmon and steelhead determined to have not been eaten at the HOR study area. Juvenile Chinook salmon had a consistent downstream migratory pattern, but steelhead swam upstream on occasion and even had some looping patterns. The similarity between steelhead behavior and predator behavior was at times difficult to distinguish. Thus, many steelhead may have been inappropriately classified as eaten. It is hypothesized that the statistical difference between juvenile Chinook salmon and steelhead proportion eaten was not because of "real" differences between the species, but because of misclassification errors in assigning predation to steelhead two-dimensional tracks. This hypothesis was supported by the observation that, after "eaten" tags were removed, juvenile Chinook salmon and steelhead P_E was not different (Table 6-39).

Table 6-54
Statistics for Proportion Eaten for Chinook Salmon and Steelhead in 2011

Statistic	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^{2a}	P-Value[a]
Mean Sample Proportion Eaten[a]	0.087	0.243	-15.6	13.463	0.0002
Standard Deviation[a]	0.091	0.238			
Samples (n)[a]	53	93			
Proportion Eaten[b]	0.101	0.240			
Standard Error[b]	0.009	0.019			

Notes: n = number of samples.

[a] Sample proportion eaten parameters are those derived from the proportion eaten of each group of fish that arrived at the HOR study area forming a single sample (see Section 5.2.1 in Chapter 5, "Methods," for the definition of a sample).

[b] Population proportion eaten parameters are those derived from the grand total eaten divided by the total number of tags in juvenile Chinook salmon (see definition in Section 5.3.1 in Chapter 5, "Methods").

Source: Present study

2012 RESULTS

Chinook Salmon

In 2012, 39.3% of the tagged juvenile Chinook salmon were identified as having been eaten (Table 6-55). This was the highest proportion eaten observed in this study for any treatment/year combination, and was examined further in relation to the barrier treatments (see "Comparison of 2009 [BAFF On], 2010 [BAFF On], 2011[No Barrier], and 2012 [Rock Barrier] Conditions," below).

Table 6-55
Statistics for Proportion Eaten, 2009–2012

Sample Proportion Eaten

Treatment—Year	Proportion Eaten[1]	Standard Deviation[1]	Number of Samples (n)[1]	Statistical Grouping[1]
BAFF On—2009	0.290	0.216	21	ab
BAFF On—2010	0.217	0.217	19	ab
No Barrier—2011	0.087	0.091	53	a
Rock Barrier—2012	0.382	0.321	27	b

Population Proportion Eaten

Treatment—Year	Proportion Eaten[2]	Standard Error (SE)[2]
BAFF On—2009	0.309	0.030
BAFF On—2010	0.310	0.030
No Barrier—2011	0.101	0.009
Rock Barrier—2012	0.394	0.035

Notes: BAFF = bio-acoustic fish fence; n = number of samples

[1] Sample proportion eaten parameters are those derived from the proportion eaten of each group of fish that arrived at the HOR study area forming a single sample (see Section 5.2.1 in Chapter 5, "Methods," for the definition of a sample).

[2] Population proportion eaten parameters are those derived from the grand total eaten divided by the total number of tags in juvenile Chinook salmon (see definition in Section 5.3.1 in Chapter 5, "Methods").

Source: Present study

The proportion of tagged juvenile Chinook salmon classified as having been eaten at the HOR study area under different ambient light levels supported the hypothesis that the large difference in O_E, between low-light and high-light conditions, was due to greater predation on juvenile Chinook salmon during the day (see Section 6.1.7). In high-light conditions, the mean proportion of tagged juvenile Chinook salmon that were determined to have been eaten at the HOR study area was 42.3 percentage points greater than the proportion determined to have been eaten in low light (Table 6-56). A large difference in predation rates between low and high light was expected because the predators were primarily visual, and was one of the main hypotheses examined with GLM analysis (see Section 6.2.2, "Probability of Predation [Generalized Linear Modeling]"). This also is discussed in Section 7.2, "Predation on Juvenile Salmonids Including Barrier Effects," in Section 7, "Discussion".

Table 6-56
Statistics for Sample Proportion of Chinook Salmon Tags Eaten at Low and High Ambient Light Levels in 2012

Statistic	Low Ambient Light (<5.4 lux)	High Ambient Light (≥5.4 lux)	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.131	0.554	-42.3	12.204	0.0005
Standard Deviation	0.203	0.271			
Minimum	0.000	0.158			
Maximum	0.500	1.000			
Samples (n)	11	16			

Note: n = number of samples
Source: Present study

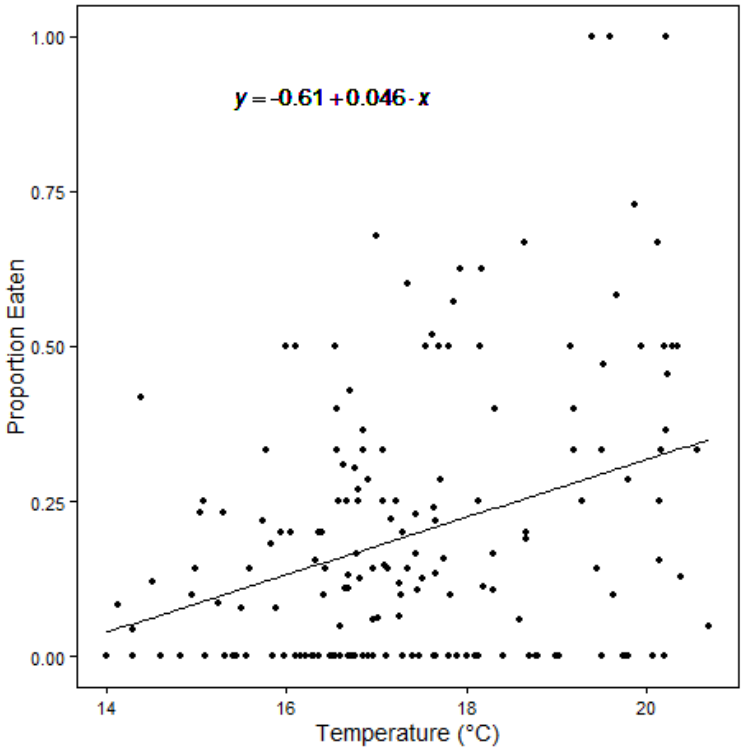
Steelhead

Of the five tagged steelhead that arrived at the HOR study area in 2012, one was eaten in the study area, so the proportion eaten was 0.200.

WATER TEMPERATURE AND TURBIDITY EFFECTS ON PROPORTION EATEN

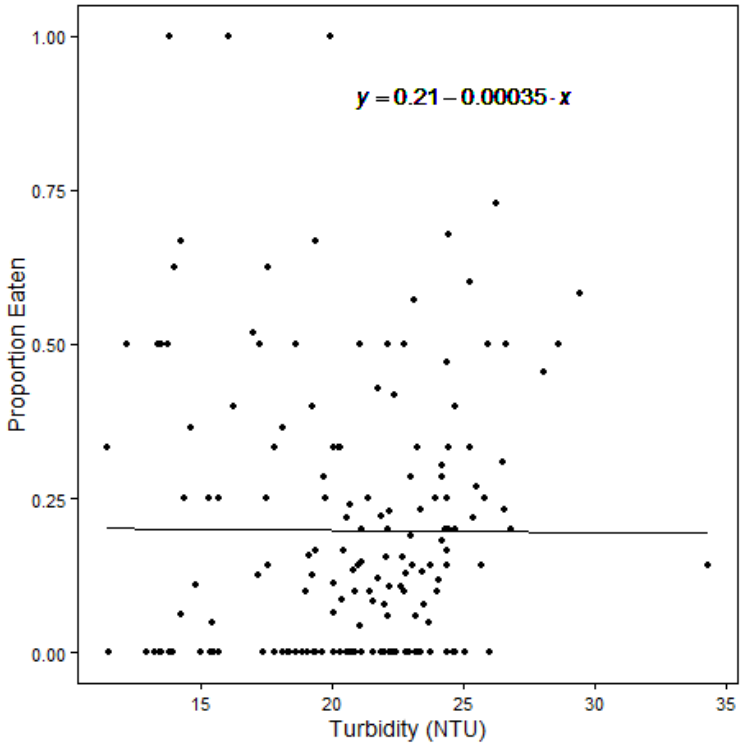
Samples from all years were considered together, and mean sample water temperature was positively correlated with proportion of juvenile Chinook salmon eaten (Spearman's $\rho = 0.264$, $P = 0.0005$, Figure 6-9). It was hypothesized that as water temperatures moved toward critically warmer temperatures for juvenile Chinook salmon (Table 3-4 in Section 3.3.1 of Section 3, "Physical Parameters"), predators gained an advantage over the juvenile salmonids in swimming performance and survival. It is also possible that increased water temperatures led to greater bioenergetic demands for prey consumption, thus increasing predation pressure at the warmer temperatures.

Similar to water temperature, turbidity samples from all years were considered together. In contrast to the effect of water temperature, turbidity was not correlated with proportion eaten for juvenile Chinook salmon (Spearman's $\rho = 0.098$, $P = 0.2034$, Figure 6-10). Further examination of water temperature and turbidity effects is provided with the GLM of predation probability (see Section 6.2.2, "Probability of Predation [Generalized Linear Modeling]").



Source: Present study

Figure 6-9 Sample Mean Temperatures and Proportion of Tagged Juvenile Chinook Salmon Eaten During Fish Release Periods from 2009–2012 with Equation of Fitted Line Shown



Source: Present study

Figure 6-10 Sample Mean Turbidities and Proportion of Tagged Juvenile Chinook Salmon Eaten During Fish Release Periods from 2009–2012 with Equation of Fitted Line Shown

COMPARISON OF 2009 (BAFF ON), 2010 (BAFF ON), 2011(NO BARRIER), AND 2012 (ROCK BARRIER) CONDITIONS

Proportion eaten was different between barrier treatments at the HOR study area (Kruskal-Wallis $X^2 = 20.505$, P-value = 0.0001). Hypothesis H_{10} was rejected. The BAFF showed no significant difference in proportion eaten in 2009 compared to 2010 (Table 6-52); therefore, the "BAFF On—2009" statistics were grouped with the "BAFF On—2010" statistics (Table 6-55). Because the data did not meet the assumptions of ANOVA, three nonparametric two-sample comparisons were made between treatments: 2010 compared to 2011; 2010 compared to 2012; and 2011 compared to 2012. As noted previously, the critical alpha for these comparisons was 0.0167. Only the two-sample comparison of 2011 vs. 2012 was significant (Kruskal-Wallis $X^2 = 77.938$, P-value <0.0001) (Table 6-55).

Among the three treatment/year types, "No Barrier—2011" produced a smaller proportion of tagged juveniles eaten (Table 6-55) compared to 2012. However, in 2011 the highest discharges were exhibited of all years studied (Appendix D, "Transit Speed Analyses," Table D-13). It was hypothesized that high discharges led to high ACVs, and these high ACVs reduced the proportion eaten by reducing predator/prey encounters. Other potential mechanisms are discussed in Section 7.1, "Predation on Juvenile Salmonids Including Barrier Effects," and Section 7.2, "Predation on Juvenile Salmonids Including Barrier Effects," in Section 7, "Discussion".

The proportion of tagged juvenile Chinook salmon that did not arrive at the HOR study area after release provided additional information about survival and predation for each year (Table 6-57). In 2009, 44.6% of the tagged juvenile Chinook salmon did not arrive at the study area, which indicated that the tags may have experienced a high predation rate prior to encountering the BAFF, and/or were more vulnerable to predation due to tag burden. In contrast, in 2010, just 11.2% of the tagged juvenile Chinook salmon did not arrive. In 2011, the high-discharge year, only a subset of tags was analyzed and so it is not possible to make inferences regarding the proportion of fish that never arrived at the HOR study area. The 2012 statistics included the highest proportion of tags eaten (39.3%), and also the highest percentage of tags released that never arrived (53.9%). Thus, it was hypothesized that the high rate of 2012 predation was not due solely to the presence of the physical rock barrier, but also was influenced by other factors contributing to greater predator numbers or better predator capture success in 2012 than in 2011 (see Sections 6.3.2, "Hydroacoustic Data," and 7.3.3, "Changes in Density of Predatory Fishes").

Table 6-57
Statistics for Chinook Salmon Tags Released and Arrived, 2009–2012

Treatment—Year	Released (n)	Arrived (n)	Never Arrived (n)	Proportion Never Arrived
BAFF—2009	960	532	428	0.446
BAFF—2010	508	451	57	0.112
No Barrier—20111	—	—	—	—
Rock Barrier—2012	419	193	226	0.539

Notes: BAFF = bio-acoustic fish fence; n = number of samples

[1] Only a subset of data were processed in 2011 and so the proportion not arriving in the study area is unknown.

Source: Present study

6.2.2 PROBABILITY OF PREDATION (GENERALIZED LINEAR MODELING)

CHINOOK SALMON

Of the 2,244 tagged juvenile Chinook salmon entering the HOR study area from 2009 through 2012, it was estimated that 422 were preyed upon (0.188, or approximately 19%) (Table 6-58). A lower proportion of juvenile Chinook salmon were preyed upon with the non-physical barrier (BAFF) turned off in 2009 and 2010 (0.182), compared to a noticeably higher proportion of juveniles that were preyed upon with the non-physical barrier turned on (0.310) and with the 2012 physical rock barrier (0.394). Approximately 0.10 of juveniles were preyed upon with no barrier (2011), which coincided with appreciably higher SJL discharge (mean of approximately 5,000 cfs) than in other years (mean of approximately 1,600 to 1,900 cfs). The proportion of juvenile Chinook salmon that were preyed upon was lower in the dark (<5.4 lux) than in the light (≥5.4 lux), and this pattern was consistent across all barrier treatments (Table 6-58). The magnitude of difference between predation proportion in the light and dark light levels ranged from double with the non-physical barrier turned off to approximately three times greater with the physical rock barrier.

GLM and modeling averaging of the 2009, 2010, and 2012 data for juvenile Chinook salmon found good support for the ambient light level, barrier status, and small-fish density predictors of predation probability, as indicated by coefficient 95% confidence intervals excluding zero and importance greater than 0.8 (Table 6-59).

The positive coefficient for the ambient light level predictor indicates a greater predation probability with increasing light level, which allowed acceptance of hypothesis H11 for this predictor (see "Objectives and Hypotheses Related to Probability of Predation" in Section 1.2.3, "Predation on Juvenile Salmonids Including Barrier Effects"). In contrast, the positive coefficient for the small-fish density predictor was contrary to the hypothesis that predation probability would be lower with greater density of small fish (i.e., greater safety in numbers for an individual juvenile entering the HOR study area).

The coefficients for the barrier status predictor indicated that there was greater predation probability with the physical rock barrier and with the non-physical barrier turned on (for which the 95% coefficient confidence intervals excluded zero) than with the non-physical barrier turned off (which was the baseline barrier treatment in the model [i.e., a value of zero]). This led to the rejection of the null hypothesis of no difference between barrier treatment included in H11. None of the other predictors of predation probability were well supported by the GLMs, and H11 was rejected for these predictors.

The GLMs with predictors included provided a better fit to the data than the intercept-only model. The full model with all predictors was the second-ranked model (out of 128 total models) and had AIC_c of 1,258.2, in comparison to AIC_c of 1,360.4 for the intercept-only model (rank 128) (Table F-1 in Appendix F, "Model Fit and Weight Tables from Results of Predation Probability Generalized Linear Modeling").

Table 6-58
Number and Proportion of Tagged Juvenile Chinook Salmon Preyed Upon at the Head of Old River in 2009, 2010, 2011, and 2012, with Means and Standard Deviations of Environmental Variables

Barrier/ Light Level	No. of Juveniles		Predation		Juvenile Length (mm)		Small-Fish Density (No./10,000 m^3)		Discharge (cfs)		Turbidity (NTU)		Temperature (°C)	
	Total	Predation	Proportion	SE	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1. Non-physical Barrier Off	511	93	0.182	0.017	101.8	8.6	2.7	2.6	1,642.5	1,240.7	21.1	5.1	17.6	1.8
a. Dark	136	14	0.103	0.026	103.3	8.8	2.6	2.3	1,723.5	1,283.9	21.0	4.4	17.1	1.4
b. Light	375	79	0.211	0.021	101.3	8.5	2.8	2.8	1,613.1	1,225.1	21.1	5.4	17.8	1.9
2.Non-physical Barrier On	465	144	0.310	0.021	102.6	8.9	2.7	2.4	1,740.4	1,270.4	23.0	4.6	17.5	1.6
a. Dark	105	10	0.095	0.029	103.6	8.4	2.6	2.6	1,342.2	1,547.9	21.4	4.2	17.1	1.5
b. Light	360	134	0.372	0.025	102.3	9.0	2.8	2.4	1,856.5	1,154.2	23.5	4.6	17.6	1.6
3.No Barrier	1,075	109	0.101	0.009	110.1	6.2	140.8	145.2	5,117.4	268.3	21.7	1.5	16.5	1.2
a. Dark	306	9	0.029	0.010	109.5	5.8	136.1	144.6	5,042.9	266.6	21.1	1.4	16.2	1.2
b. Light	769	100	0.130	0.012	110.4	6.3	142.6	145.5	5,147.1	263.3	22.0	1.4	16.7	1.2
4.Rock Barrier	193	76	0.394	0.035	110.0	7.4	4.1	2.3	1,855.4	465.1	17.2	3.1	18.6	0.9
a. Dark	38	6	0.158	0.059	106.4	6.2	3.2	1.9	1,880.2	382.7	18.0	3.5	19.0	0.9
b. Light	155	70	0.452	0.040	110.9	7.4	4.4	2.3	1,849.3	484.0	17.0	2.9	18.5	0.9
Total	2,244	422	0.188	0.008	106.7	8.4	69.0	121.8	3,345.8	1,904.6	21.5	3.8	17.2	1.6

Notes: Shaded rows indicate data used in GLM of predation probability for juvenile Chinook salmon in 2009, 2010, and 2012.
°C = degrees Celsius; cfs = cubic feet per second; m^3 = cubic meters; mm = millimeters; No. = number; NTU = nephelometric turbidity units; SD = standard deviation; SE = standard error; Dark <5.4 lux; Light ≥5.4 lux
Source: Present study

Table 6-59
Model-Averaged Coefficients, 95% Confidence Limits, and Variable Importance for Generalized Linear Modeling of Predation Probability of Tagged Juvenile Chinook Salmon at Head of Old River in 2009, 2010, and 2012

Variable	Estimate	95% Confidence Limits		Importance
		Lower	Upper	
Ambient Light	0.108	0.072	0.144	1.00
Barrier (Non-physical Barrier On)	0.605	0.285	0.924	1.00
Barrier (Physical Rock)	0.853	0.310	1.396	1.00
Small-Fish Density	0.222	0.049	0.394	0.96
Turbidity	0.035	-0.005	0.076	0.86
Juvenile Length	0.015	-0.011	0.041	0.72
Water Temperature	0.078	-0.059	0.215	0.71
Discharge	0.002	-0.003	0.007	0.44

Note: Barrier status coefficients are in relation to baseline estimates with the non-physical barrier turned off (Non-physical Barrier Off).
Source: Present study

The optimum threshold for the model-averaged predictor coefficients was 0.36 based on the maximum Kappa method. The Kappa statistic indicated that approximately 33% of all possible predation and survival fates were correctly predicted by the model-averaged coefficients, adjusting for correct predictions by chance. The percent of outcomes correctly classified was 73.5%. The model-averaged coefficients correctly predicted 51.4% of true positives (juveniles that had been preyed upon [i.e., sensitivity]) and 81.5% of true negatives (juveniles that had survived [i.e., specificity]), indicating a false positive classification of 19.5%. The area under ROC was 0.70, indicating that the model-averaged coefficients were at the lower end of the "acceptable discrimination" range (Hosmer and Lemeshow 2000: 162). Overall, the model-averaged predictors provided a reasonable representation of the predation probability in relation to the observed predation proportion, although the model somewhat underestimated the higher predation proportion that occurred in light conditions (Figure 6-11).

A second set of GLMs was used to assess the probability of predation on juvenile Chinook salmon for 2011 and 2012. As described in Section 5.3.2, "Probability of Predation (Generalized Linear Modeling)," this analysis included estimates of the density of large fish (greater than 30 cm TL) from mobile hydroacoustics as a potential indicator of predatory fish abundance at the HOR study area. Such estimates were not available for 2009 and 2010. These GLMs did not include barrier status as a predictor because discharge was considerably different between 2011 and 2012 and so confounded the barrier predictor. Table 6-60 summarizes the data used in this analysis. These data are a subset of the data from Table 6-58 because many juveniles had missing values for the large-fish density predictor (i.e., their entry into the study area did not coincide suitably with mobile hydroacoustic surveys).

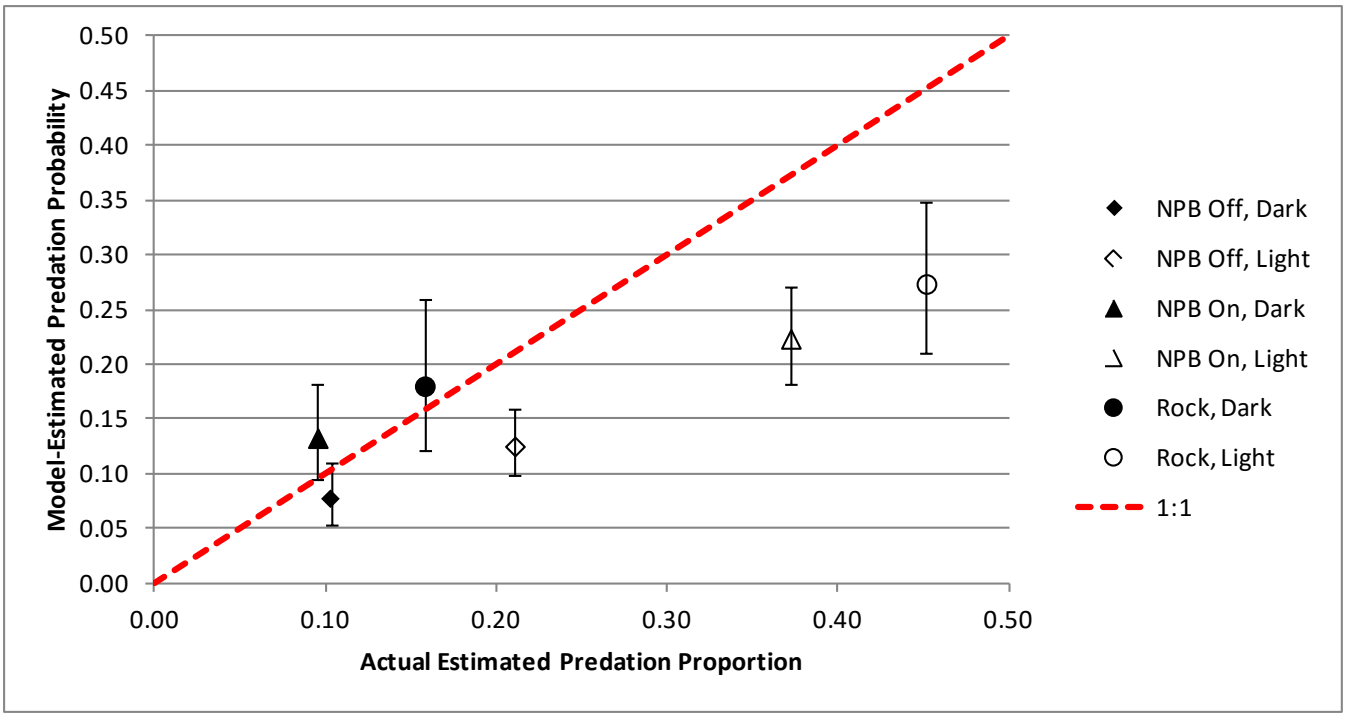
Table 6-60
Number and Proportion of Tagged Juvenile Chinook Salmon Preyed Upon at the Head of Old River in 2011 and 2012, with Means and Standard Deviations of Environmental Variables

Barrier/ Light Level	No. of Juveniles		Predation		Juvenile Length (mm)		Large-Fish Density, Down (No./10,000 m^3)		Large-Fish Density, Side (No./10,000 m^3)		Small-Fish Density (No./10,000 m^3)		Discharge (cfs)		Turbidity (NTU)		Temperature (°C)	
	Total	Predation	Proportion	SE	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1.No Barrier	797	80	0.100	0.011	109.1	5.3	4.3	2.0	1.6	0.4	157.7	151.5	5,165.5	248.2	21.7	1.3	16.1	1.1
a. Dark	240	8	0.033	0.012	108.9	5.2	3.9	2.2	1.6	0.5	142.2	150.3	5,071.5	259.1	21.0	1.2	15.9	1.1
b. Light	557	72	0.129	0.014	109.2	5.3	4.4	1.9	1.6	0.4	164.4	151.7	5,206.0	232.1	22.0	1.3	16.2	1.1
2.Rock Barrier	79	30	0.380	0.055	110.5	7.6	144.3	143.7	6.1	2.1	3.7	1.1	1,850.0	478.1	16.7	2.9	18.7	1.0
a. Dark	15	3	0.200	0.103	105.5	5.2	136.2	149.4	6.0	2.1	4.1	1.4	1,976.0	328.7	17.4	2.6	18.8	1.0
b. Light	64	27	0.422	0.062	111.7	7.6	146.2	143.4	6.1	2.1	3.6	0.9	1,820.4	504.3	16.5	3.0	18.7	1.1
Total	876	110	0.126	0.011	109.3	5.5	16.9	58.8	2.0	1.5	143.8	151.1	4,866.5	989.7	21.2	2.1	16.4	1.3

Notes: °C = degrees Celsius; cfs = cubic feet per second; m^3 = cubic meters; mm = millimeters; No. = number; NTU = nephelometric turbidity units; SD = standard deviation; SE = standard error; Dark <5.4 lux; Light ≥5.4 lux.

Shaded rows indicate data used in GLM of predation probability for juvenile Chinook salmon in 2011 and 2012.

Source: Present study



Note: NPB = non-physical barrier

Source: Present study

Figure 6-11 **Probability of Predation (with 95% Confidence Interval) of Tagged Juvenile Chinook Salmon at Head of Old River, Estimated from GLM in Relation to Observed Predation Proportion, for Various Combinations of Barrier Status and Light/Dark Conditions in 2009, 2010, and 2012**

Model-averaging indicated that only ambient light level and turbidity were well-supported predictors of the probability of predation on juvenile Chinook salmon in 2011 and 2012 (Table 6-61). The signs of the coefficients indicated support for hypothesis H12 that predation probability would be greater under higher visibility conditions (lower turbidity, higher light levels). None of the other predictors were well-supported from model-averaging (coefficient 95% confidence intervals included zero and importances were less than 0.8); hypothesis H12 was rejected for these predictors.

The GLMs including predictors provided a better fit to the data than the intercept-only model, with the full model having AIC_c = 593.3 (model rank = 17 out of 256 models) and the intercept-only model having AIC_c = 664.0 (ranked last out of all models) (Table F-2 in Appendix F, "Model Fit and Weight Tables from Results of Predation Probability Generalized Linear Modeling"). The optimum threshold for the model-averaged predictor coefficients was 0.18 based on the maximum Kappa method. The Kappa statistic indicated that approximately 29% of all possible predation and survival fates were correctly predicted by the model-averaged coefficients, adjusting for correct predictions by chance. The percent correctly classified was 82.8%. The model-averaged coefficients correctly predicted 43.6% of true positives (i.e., sensitivity) and 88.4% of true negatives (i.e., specificity), for a false positive classification of 11.6%. The area under the ROC was 0.73, which was slightly greater than the GLMs of predation probability in 2009, 2010, and 2012, and indicated that the model-averaged coefficients were within the "acceptable discrimination" range (Hosmer and Lemeshow 2000:162).

Table 6-61
Model-Averaged Coefficients, 95% Confidence Limits, and Variable Importance for the Generalized Linear Modeling of Predation Probability of Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Variable	Estimate	95% Confidence Limits		Importance
		Lower	Upper	
Ambient Light	0.127	0.071	0.182	1.00
Turbidity	-0.270	-0.412	-0.129	1.00
Water Temperature	0.171	-0.105	0.448	0.74
Large-Fish Density (Down)	-0.126	-0.467	0.215	0.49
Juvenile Length	0.012	-0.024	0.047	0.44
Small-Fish Density	0.038	-0.109	0.184	0.39
Large-Fish Density (Side)	0.164	-0.580	0.908	0.35
Discharge	0.000	-0.005	0.005	0.31

Source: Present study

STEELHEAD

A total of 525 tagged juvenile steelhead entered the HOR study area in 2011 and 2012, and 126 (0.24, or 24%) were estimated to have been preyed upon (Table 6-62). Only five juveniles entered the area in 2012 when the physical rock barrier was present, and one was preyed upon. For 2011 (no barrier), the predation proportion was higher in light (0.261) than dark (0.182) conditions.

Only 2011 data were included in the GLM analysis for steelhead predation probability at the HOR study area. The desire to include large-fish density data from mobile hydroacoustics as an indication of predator abundance reduced sample size because steelhead entry did not always coincide with mobile hydroacoustics. Table 6-63 summarizes the data included in the steelhead GLM of predation probability for 163 steelhead entering the study area in 2011. GLMs with predictors included did not produce a better fit to the data than the intercept-only model. The full model with all predictors included ranked 250 out of 256 models, with an AIC_c of 199.0, which was higher than the intercept-only model (AIC_c = 192.1, rank = 16) (Table F-3 in Appendix F, "Model Fit and Weight Tables from Results of Predation Probability Generalized Linear Modeling"). The lack of support for all predictors of steelhead predation probability included in the GLM was also evident from model-averaged coefficients, for which all 95% confidence intervals included zero and importances were all less than 0.8.

Table 6-62
Number and Proportion of Tagged Juvenile Steelhead Preyed Upon at the Head of Old River in 2011 and 2012, with Means and Standard Deviations of Environmental Variables

	No. of Juveniles		Predation		Juvenile Length (mm)		Small-Fish Density (No./10,000 m^3)		Discharge (cfs)		Turbidity (NTU)		Temperature (°C)	
Barrier/Light	Total	Predation	Proportion	SE	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2011 No Barrier	520	125	0.240	0.019	282.2	23.3	69.3	119.7	5,424.4	857.7	21.8	2.3	16.4	1.1
a. Dark	137	25	0.182	0.033	279.5	20.4	80.5	131.9	5,603.4	947.8	20.9	1.8	16.6	1.2
b. Light	383	100	0.261	0.022	283.1	24.2	65.3	115.0	5,360.4	814.9	22.2	2.4	16.3	1.0
2012 Rock Barrier	5	1	0.200	0.179	242.8	14.0	3.6	0.6	1,320.8	635.2	15.0	3.2	19.2	0.3
a. Dark	2	0	0.000	0.000	232.0	2.8	3.7	0.3	1,223.0	589.7	13.2	1.0	19.2	0.6
b. Light	3	1	0.333	0.272	250.0	14.0	3.5	0.8	1,386.0	785.6	16.2	3.9	19.3	0.2
Total	525	126	0.240	0.019	281.8	23.6	68.7	119.3	5,385.4	943.9	21.8	2.4	16.4	1.1

Notes: °C = degrees Celsius; cfs = cubic feet per second; m^3 = cubic meters; mm = millimeters; No. = number; NTU = nephelometric turbidity units; SD = standard deviation; SE = standard error; Dark <5.4 lux; Light ≥5.4 lux

Source: Present study

Table 6-63
Number and Proportion of Tagged Juvenile Steelhead Preyed Upon at the Head of Old River in 2011 and 2012, with Means and Standard Deviations of Environmental Variables

	No. of Juveniles		Predation		Juvenile Length (mm)		Large-Fish Density, Down (No./10,000 m^3)		Large-Fish Density, Side (No./10,000 m^3)		Small-Fish Density (No./10,000 m^3)		Discharge (cfs)		Turbidity (NTU)		Temperature (°C)	
Barrier/Light	**Total**	**Predation**	**Proportion**	**SE**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
2011 No Barrier	163	44	0.270	0.035	284.9	24.3	4.6	2.0	1.8	0.6	132.8	143.8	5,116.3	239.4	22.1	1.3	16.2	0.9
a. Dark	44	8	0.182	0.058	282.3	22.3	4.9	1.9	1.7	0.5	156.6	157.0	5,036.4	278.2	21.2	1.0	16.0	0.9
b. Light	119	36	0.303	0.042	285.9	25.0	4.6	2.1	1.8	0.6	124.0	138.3	5,145.8	217.4	22.4	1.3	16.2	0.9
2012 Rock Barrier	4	0	0.000	0.000	238.5	11.8	311.2	19.5	8.3	0.1	3.8	0.2	1,133.5	551.5	13.7	1.8	19.2	0.3
a. Dark	2	0	0.000	0.000	232.0	2.8	320.9	27.5	8.3	0.1	3.7	0.3	1,223.0	589.7	13.2	1.0	19.2	0.6
b. Light	2	0	0.000	0.000	245.0	15.6	301.4	0.0	8.3	0.0	3.9	0.0	1,044.0	729.7	14.3	2.8	19.2	0.1
Total	167	44	0.263	0.034	283.8	25.1	12.0	47.1	1.9	1.2	129.7	143.5	5,020.9	659.2	21.9	1.8	16.2	1.0

Notes: °C = degrees Celsius; cfs = cubic feet per second; m^3 = cubic meters; mm = millimeters; No. = number; NTU = nephelometric turbidity units; SD = standard deviation; SE = standard error; Dark <5.4 lux; Light ≥5.4 lux

Shaded rows indicate data used in GLM of predation probability for juvenile steelhead in 2011.

Source: Present study

6.3 BEHAVIOR AND DENSITY CHANGES IN PREDATORY FISH

6.3.1 DATA FROM TAGGED PREDATORY FISH

OVERVIEW OF TAGGED PREDATORY FISH

One hundred predatory fish were captured, acoustically tagged, and released at the HOR study area from 2009 through 2012 (Table 6-64). However, only 82 were detected post-tagging within the acoustic arrays, which, when combined with an additional two fish tagged elsewhere in the system (both striped bass in 2010), provided an overall total of 84 fish for analysis. Only two fish were tagged in 2009 (largemouth bass tag code 4306 and striped bass tag code 4222), and only one fish was tagged in 2010 (striped bass tag code 2472). In 2011, 37 fish were tagged, of which three were largemouth bass (290 to 300 mm FL), 30 were striped bass (340 to 686 mm FL), and four were white catfish (255 to 375 mm FL). In 2012, 42 fish were tagged, of which six were channel catfish (305 to 625 mm TL; one released into Old River below the HOR physical rock barrier, the remainder San Joaquin River side of the physical rock barrier), 13 were largemouth bass (307 to 440 mm TL; six released into Old River below the physical rock barrier, the remainder into the San Joaquin River), 22 were striped bass (310 to 667 mm TL; 15 released into Old River below the physical rock barrier, the remainder upstream of the physical rock barrier), and one was a white catfish (320 mm TL, released into the San Joaquin River) (Table 6-64).

In the following sections describing the detailed results related to tagged predatory fish, fish tagged in 2012 are referred to either as being released into the HOR if they were released downstream of the physical rock barrier, or released into the San Joaquin River if they were released upstream of the physical rock barrier (either into the San Joaquin River or into Old River upstream).

RESIDENCE TIME

The approximate duration that tagged predatory fish spent within the detectable distance of the acoustic arrays at the HOR study area ranged from 0.01 hour (striped bass tag code 3366 in 2011) to 622 hours (white catfish tag code 3408 in 2011) (Table 6-64). There were considerable ranges in the length of time spent at the HOR study area by each species: channel catfish (0.08 to 71.5 hours), largemouth bass (0.11 to 242.6 hours), striped bass (0.01 to 282.6 hours), and white catfish (1.0 to 621.9 hours).

The percentage of dates between tagging/release and deactivation of the acoustic array was assessed to account for two factors: capture and tagging events occurring over a number of weeks (which affected the potential maximum duration that a fish could spend at the HOR study area), and the observation that some fish were detected on many dates but had relatively few positive detections by the array. Striped bass generally were detected on the smallest percentage of possible dates between tagging/release and acoustic array deactivation of the four predatory fish species. Striped bass had bootstrapped mean percentages of dates detected in all years of 10% to 20%, with bootstrapped 95% confidence intervals ranging from around 8% to 14% for 2011, and 2012 Old River releases from 4% to 38% for 2012 San Joaquin River releases (Figure 6-12).

The 95% confidence intervals of the percentage of dates when striped bass were detected in 2009 and 2010 (4.5 to 26%), 2011, and 2012 (Old River releases) did not overlap the 95% confidence intervals for largemouth bass in 2012 (San Joaquin River releases: 33 to 90%) or white catfish in 2011 (35 to 100%). They also had very little overlap with the 95% confidence interval for channel catfish released into Old River in 2012 (22 to 61%) (Figure 6-12).

Table 6-64
Tagged Predatory Fish at the Head of Old River, 2009-2012

Species	Length (mm FL unless noted in "Comments")	Tag Code	Tagging/ Release Date	Dates Detected in Study Area	Approx. Duration in Study Area (Hours)	Release Area	Comments
Channel Catfish	515	2511	4/22/2012	NA	Undetected	SJ River	Total Length
Channel Catfish	460	2847	5/9/2012	5/9/2012, 5/14/2012, 5/20/2012 to 5/24/2012, 5/26/2012, 5/27/2012	6.57	SJ River	Total Length
Channel Catfish	305	2490	5/20/2012	5/20/2012	4.76	SJ River	Total Length
Channel Catfish	625	2112	5/22/2012	5/22/2012	0.08	Old River	Total Length
Channel Catfish	473	2952	5/22/2012	5/22/2012, 5/23/2012, 5/27/2012, 5/29/2012	10.69	SJ River	Total Length
Channel Catfish	545	2763	5/23/2012	5/23/2012 to 5/28/2102	71.54	SJ River	Total Length
Channel Catfish	535	2994	5/23/2012	5/23/2012, 5/24/2012, 5/31/2012	3.54	SJ River	Total Length
Largemouth Bass	315	4306	5/6/2009	5/06/2009 to 5/16/2009	88.17		
Largemouth Bass	300	3324	5/24/2011	6/9/2011 to 6/11/2011, 6/13/2011, 6/15/2011 to 6/18/2011, 6/20/2011 to 6/22/2011	17.09		
Largemouth Bass	290	3436	5/24/2011	5/24/2011	0.11		
Largemouth Bass	320	3464	5/24/2011	NA	Undetected		
Largemouth Bass	290	3492	5/24/2011	5/25/2011 to 5/28/2011, 5/30/2011 to 6/1/2011, 6/7/2011, 6/9/2011, 6/13/2011, 6/15/2011, 6/16/2011, 6/21/2011, 6/22/2011	20.86		
Largemouth Bass	350	2049	4/22/2012	NA	Undetected	SJ River	Total Length
Largemouth Bass	440	2280	4/22/2012	4/23/2012, 4/27/2012, 5/17/2012, 5/18/2012	3.09	SJ River	Total Length
Largemouth Bass	440	2091	4/29/2012	4/29/2012, 5/10/2012, 5/12/2012 to 5/20/2012	96.61	Old River	Total Length
Largemouth Bass	360	2742	4/29/2012	4/29/2012, 5/5/2012	3.61	Old River	Total Length
Largemouth Bass	323	2322	5/6/2012	5/6/2012 to 5/9/2012, 5/11/2012 to 5/31/2012	242.57	Old River	Total Length
Largemouth Bass	350	2133	5/15/2012	5/15/2012	0.70	Old River	Total Length
Largemouth Bass	316	3078	5/18/2012	5/18/2012 to 5/27/2012	95.27	SJ River	Total Length
Largemouth Bass	420	2826	5/19/2012	NA	Undetected	Old River	Total Length
Largemouth Bass	335	3057	5/19/2012	5/19/2012	1.68	Old River	Total Length

Table 6-64
Tagged Predatory Fish at the Head of Old River, 2009-2012

Species	Length (mm FL unless noted in "Comments")	Tag Code	Tagging/ Release Date	Dates Detected in Study Area	Approx. Duration in Study Area (Hours)	Release Area	Comments
Largemouth Bass	323	2028	5/20/2012	5/20/2012 to 5/31/2012	182.51	SJ River	Total Length
Largemouth Bass	380	2196	5/20/2012	5/20/2012	0.45	Old River	Total Length
Largemouth Bass	395	2259	5/20/2012	5/20/2012 to 5/22/2012	39.13	SJ River	Total Length
Largemouth Bass	374	2070	5/22/2012	5/22/2012, 5/25/2012	3.07	SJ River	Total Length
Largemouth Bass	316	2301	5/22/2012	NA	Undetected	SJ River	Total Length
Largemouth Bass	307	2721	5/22/2012	5/22/2012 to 5/31/2012	192.89	SJ River	Total Length
Largemouth Bass	345	2532	5/23/2012	5/23/2012 to 5/31/2012	48.18	SJ River	Total Length
Largemouth Bass	332	3141	5/24/2012	NA	Undetected	SJ River	Total Length
Striped Bass	370	4222	5/12/2009	5/12/2009	0.26		
Striped Bass	406	2024	4/4/2010	4/28/2010, 5/7/2010	0.61		Tagged downstream of the HOR study area in San Joaquin River near Weston Ranch
Striped Bass	480	2976	5/5/2010	5/22/2010	0.54		Tagged downstream of the HOR study area at Tracy Fish Facility
Striped Bass	508	2472	5/16/2010	5/16/2010 to 5/18/2010	3.04		
Striped Bass	425	2136	5/14/2011	NA	Undetected		
Striped Bass	570	2234	5/14/2011	5/14/2011, 5/15/2011	7.14		
Striped Bass	405	2206	5/19/2011	5/19/2011	0.13		
Striped Bass	565	2262	5/19/2011	5/19/2011 to 5/28/2011	38.77		
Striped Bass	340	3422	5/19/2011	5/19/2011	0.20		
Striped Bass	405	2556	5/20/2011	5/20/2011, 5/28/2011	0.60		
Striped Bass	360	3338	5/20/2011	5/20/2011	0.07		
Striped Bass	330	3478	5/20/2011	NA	Undetected		
Striped Bass	415	2290	5/21/2011	5/21/2011, 5/23/2011 to 5/25/2011, 6/9/2011	5.90		

Table 6-64
Tagged Predatory Fish at the Head of Old River, 2009-2012

Species	Length (mm FL unless noted in "Comments")	Tag Code	Tagging/ Release Date	Dates Detected in Study Area	Approx. Duration in Study Area (Hours)	Release Area	Comments
Striped Bass	540	3060	5/21/2011	5/21/2011	0.66		
Striped Bass	405	3366	5/21/2011	5/21/2011	0.01		
Striped Bass	381	3380	5/22/2011	5/22/2011, 5/24/2011	0.19		
Striped Bass	390	3450	5/24/2011	5/24/2011, 5/27/2011, 6/22/2011	0.60		
Striped Bass	490	3074	5/26/2011	5/26/2011	0.07		
Striped Bass	350	2122	6/1/2011	6/1/2011	0.07		
Striped Bass	399	3172	6/2/2011	NA	Undetected		
Striped Bass	686	3382	6/2/2011	6/2/2011	0.09		
Striped Bass	360	3200	6/6/2011	NA	Undetected		
Striped Bass	385	3270	6/6/2011	6/6/2011	0.30		
Striped Bass	461	3298	6/6/2011	6/6/2011	7.40		
Striped Bass	544	2094	6/7/2011	NA	Undetected		
Striped Bass	445	2486	6/7/2011	6/7/2011, 6/8/2011	6.35		
Striped Bass	440	3340	6/7/2011	6/7/2011	12.99		
Striped Bass	374	3088	6/8/2011	6/8/2011, 6/9/2011	24.50		
Striped Bass	433	3144	6/8/2011	6/8/2011	0.06		
Striped Bass	455	3186	6/8/2011	6/8/2011	0.03		
Striped Bass	400	3242	6/8/2011	6/8/2011	0.05		
Striped Bass	410	3158	6/9/2011	6/9/2011	0.04		
Striped Bass	370	3284	6/9/2011	6/9/2011, 6/10/2011	0.81		
Striped Bass	395	2178	6/13/2011	6/13/2011	0.09		
Striped Bass	430	2248	6/13/2011	6/13/2011, 6/14/2011	2.44		
Striped Bass	420	2332	6/13/2011	NA	Undetected		
Striped Bass	390	3102	6/13/2011	NA	Undetected		

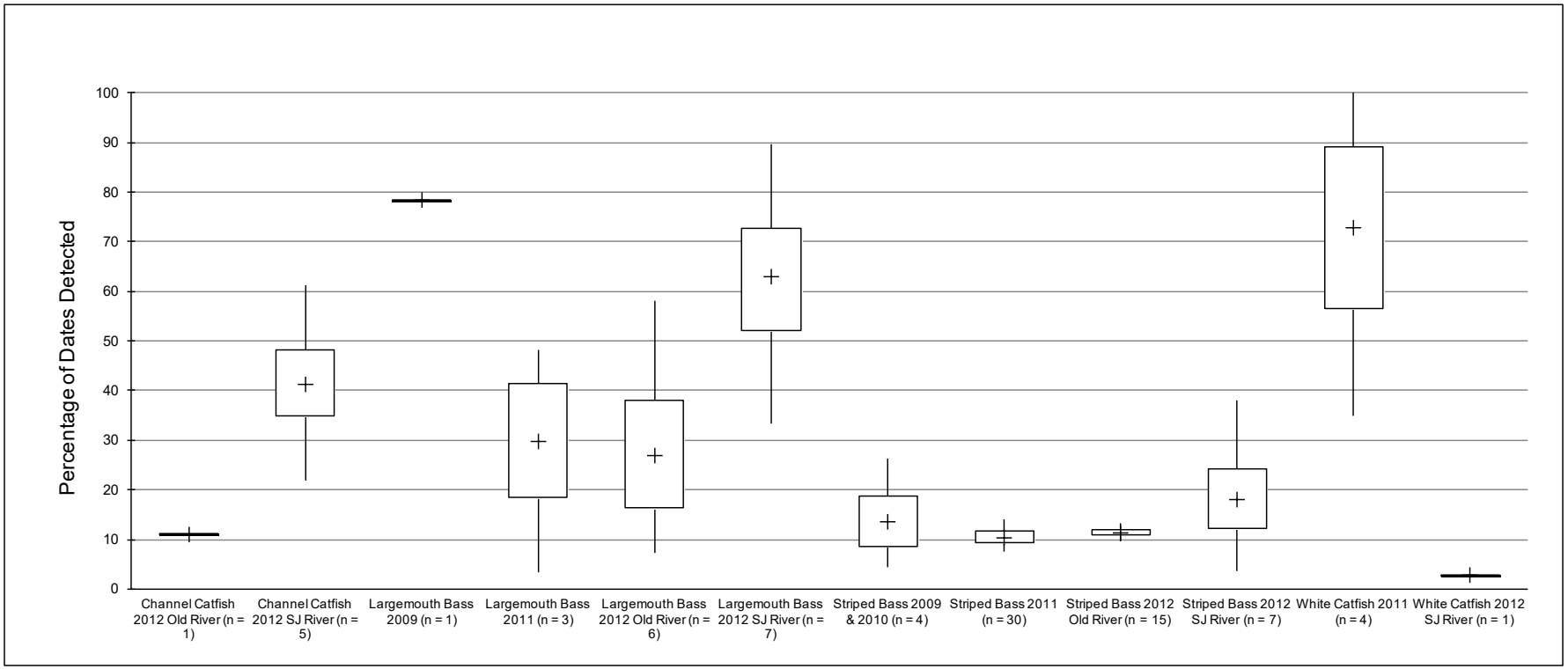
Table 6-64
Tagged Predatory Fish at the Head of Old River, 2009-2012

Species	Length (mm FL unless noted in "Comments")	Tag Code	Tagging/ Release Date	Dates Detected in Study Area	Approx. Duration in Study Area (Hours)	Release Area	Comments
Striped Bass	385	3130	6/13/2011	NA	Undetected		
Striped Bass	390	3312	6/13/2011	6/13/2011	0.07		
Striped Bass	580	3354	6/13/2011	6/13/2011	0.03		
Striped Bass	410	3368	6/13/2011	NA	Undetected		
Striped Bass	450	3228	6/14/2011	6/14/2011, 6/16/2011	7.57		
Striped Bass	620	3256	6/15/2011	6/15/2011, 6/16/2011, 6/18/2011	11.95		
Striped Bass	400	2007	4/24/2012	4/24/2012, 4/25/2012	0.66	SJ River	Total Length
Striped Bass	450	2238	4/24/2012	NA	Undetected	SJ River	Total Length
Striped Bass	405	2469	4/24/2012	4/24/2012	0.04	SJ River	Total Length
Striped Bass	411	2700	4/27/2012	4/27/2012	0.99	SJ River	Total Length
Striped Bass	398	2973	4/29/2012	4/29/2012, 5/1/2012, 5/2/2012, 5/25/2012	12.39	Old River	Total Length
Striped Bass	504	2154	5/6/2012	5/6/2012, 5/15/2012 to 5/26/2012, 5/29/2012 to 5/31/2012	282.60	SJ River	Total Length
Striped Bass	405	2385	5/6/2012	5/6/2012	0.05	SJ River	Total Length
Striped Bass	415	2553	5/6/2012	5/6/2012, 5/7/2012	8.53	Old River	Total Length
Striped Bass	420	2616	5/6/2012	5/6/2012	0.02	SJ River	Total Length
Striped Bass	450	2784	5/15/2012	5/15/2012	0.13	Old River	Total Length
Striped Bass	425	3015	5/15/2012	5/15/2012	8.73	Old River	Total Length
Striped Bass	433	2364	5/16/2012	5/16/2012	0.42	Old River	Total Length
Striped Bass	410	2595	5/16/2012	5/16/2012, 5/17/2012	12.14	Old River	Total Length
Striped Bass	310	2427	5/20/2012	5/20/2012, 5/21/2012	20.09	Old River	Total Length
Striped Bass	400	2658	5/21/2012	5/21/2012	1.61	Old River	Total Length
Striped Bass	355	2217	5/22/2012	5/22/2012	0.18	Old River	Total Length
Striped Bass	667	2343	5/22/2012	5/22/2012 to 5/25/2012	43.02	SJ River	Total Length

Table 6-64
Tagged Predatory Fish at the Head of Old River, 2009-2012

Species	Length (mm FL unless noted in "Comments")	Tag Code	Tagging/ Release Date	Dates Detected in Study Area	Approx. Duration in Study Area (Hours)	Release Area	Comments
Striped Bass	409	2889	5/22/2012	5/22/2012	0.23	Old River	Total Length
Striped Bass	401	3120	5/22/2012	5/22/2012	0.35	Old River	Total Length
Striped Bass	330	2448	5/24/2012	5/24/2012	0.20	Old River	Total Length
Striped Bass	440	2574	5/24/2012	5/24/2012	7.40	Old River	Total Length
Striped Bass	330	2679	5/24/2012	5/24/2012	0.11	Old River	Total Length
Striped Bass	325	2910	5/24/2012	5/24/2012	0.23	Old River	Total Length
White Catfish	255	3352	5/25/2011	5/25/2011 to 6/22/2011	572.04		
White Catfish	286	3394	5/25/2011	5/25/2011, 5/26/2011, 6/1/2011 to 6/22/2011	412.51		
White Catfish	280	3408	5/25/2011	5/25/2011 to 6/22/2011	621.88		
White Catfish	325	2598	6/6/2011	NA	Undetected		
White Catfish	375	2346	6/7/2011	6/7/2011, 6/9/2011	1.04		
White Catfish	405	3116	6/8/2011	NA	Undetected		
White Catfish	320	2931	4/27/2012	4/27/2012	1.54	SJ River	Total Length

Notes: HOR = Head of Old River; mm = millimeters; SJ = San Joaquin
Source: Present study



Source: Present study

Figure 6-12 **Percentage of Dates when Tagged Predatory Fish Were Detected within the HOR Study Area: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**

The 95% confidence intervals of the percentage of dates detected generally overlapped for the other species/year/release location groups, probably as a result of relatively small sample size (i.e., few fish per group). Individual channel catfish (San Joaquin River release) and white catfish (Old River release) in 2012 were detected on a much lower percentage of dates than the 95% confidence intervals of dates detected for the other species/year/release location group of each of these species. The single largemouth bass tagged in 2009 was detected on nearly 80% of dates; this was within the 95% confidence interval for the 2012 San Joaquin River releases and greater than the 95% confidence intervals for 2011 (3.4 to 48%) and 2012 Old River (7 to 58%) releases of this species (Figure 6-12).

AREAS OCCUPIED AND EMIGRATION

Areas Occupied

A full summary of the percentage of total detections by zone for each of the 84 individual tagged predatory fish at the HOR study area is provided in Table 6-65. Zone location was presented in Figure 5-14 in the "Spatial Analysis" subsection of the "Data Analysis" subsection of Section 5.4.1, "Predatory Fish Acoustic Tagging." More detailed analyses were conducted only for fish with at least 1,000 detections in the study area. The following seven species/year/release location groups with more than one fish per group were evaluated:

- Channel catfish released in the San Joaquin River in 2012
- Largemouth bass released into the San Joaquin River in 2012 (i.e., upstream of the physical rock barrier)
- Largemouth bass released into the HOR in 2012 (i.e., downstream of the physical rock barrier)
- Striped bass released in 2011
- Striped bass released into the San Joaquin River in 2012 (i.e., upstream of the physical rock barrier)
- Striped bass released into the HOR in 2012 (i.e., downstream of the physical rock barrier)
- White catfish released in 2011

In addition, a summary of detections from a single largemouth bass tagged and released in 2009, as well as observations from several striped bass tagged and released in 2009 and 2010, were made in relation to the non-physical barrier (BAFF) installed in those years.

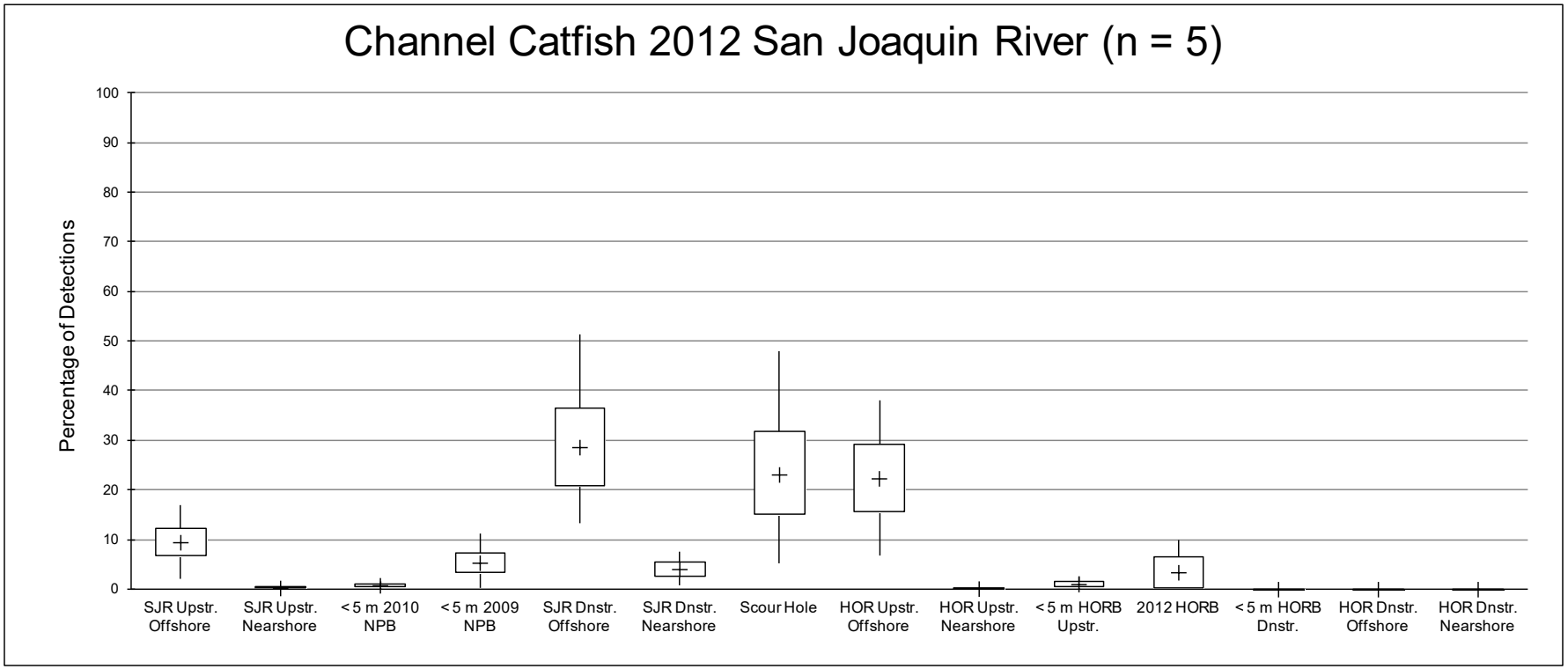
Channel Catfish

Channel catfish released on the San Joaquin River side of the physical rock barrier in 2012 (n = 5 fish) were detected most frequently at two locations (Figure 6-13):

- In the San Joaquin River downstream of the Old River divergence (San Joaquin River downstream offshore: bootstrapped mean = 29%, 95% confidence interval = 13–52%; the scour hole: bootstrapped mean = 23%, 95% confidence interval = 5–48%)
- At the HOR upstream (HOR study area upstream offshore: bootstrapped mean = 22%, 95% confidence interval = 7–38%)

Table 6-65
Percentage of Tag Detections by Zone for Predatory Fish at the Head of Old River, 2009–2012

| Species/Year/Release Site | Tag Code | Total Detections | Dates in Area First | Dates in Area Last | Zones First | Zones Last | San Joaquin River Upstream | | |



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

Figure 6-13 **Percentage of Tag Detections for Channel Catfish within Different Zones of the HOR Study Area for 2012 San Joaquin River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**

The index of zone use relative to zone size was computed as the percentage of detections divided by the percentage of grid points in each zone; values of 1 indicated that the use of the zone was exactly proportional to its size. This index indicated that use of the San Joaquin River's downstream offshore zone was proportionally greater than the zone's size (95% confidence interval = 1.4 to 5.3) (Figure 6-14). By contrast, several zones in the upstream San Joaquin River and the HOR's upstream nearshore zone were used considerably less than proportional to their size (95% confidence intervals <1).

Largemouth Bass

Largemouth bass released into the San Joaquin River in 2012 (n = 7 fish) were detected most frequently in the San Joaquin River downstream of the Old River divergence (San Joaquin River downstream offshore: bootstrapped mean = 22%, 95% confidence interval = 7 to 39%; San Joaquin River downstream nearshore: bootstrapped mean = 21%, 95% confidence interval = 9 to 35%) (Figure 6-15). This result was notable because five of these seven fish were released at the HOR just upstream of the physical rock barrier (Table 6-65).

Relative to zone size, the San Joaquin River downstream nearshore zone was used to a considerable extent by largemouth bass (95% confidence interval: 2.3 to 8.6) (Figure 6-16). Two other nearshore zones (San Joaquin River upstream nearshore and HOR upstream nearshore), as well as the San Joaquin River downstream offshore zone, also were used appreciably relative to their size.

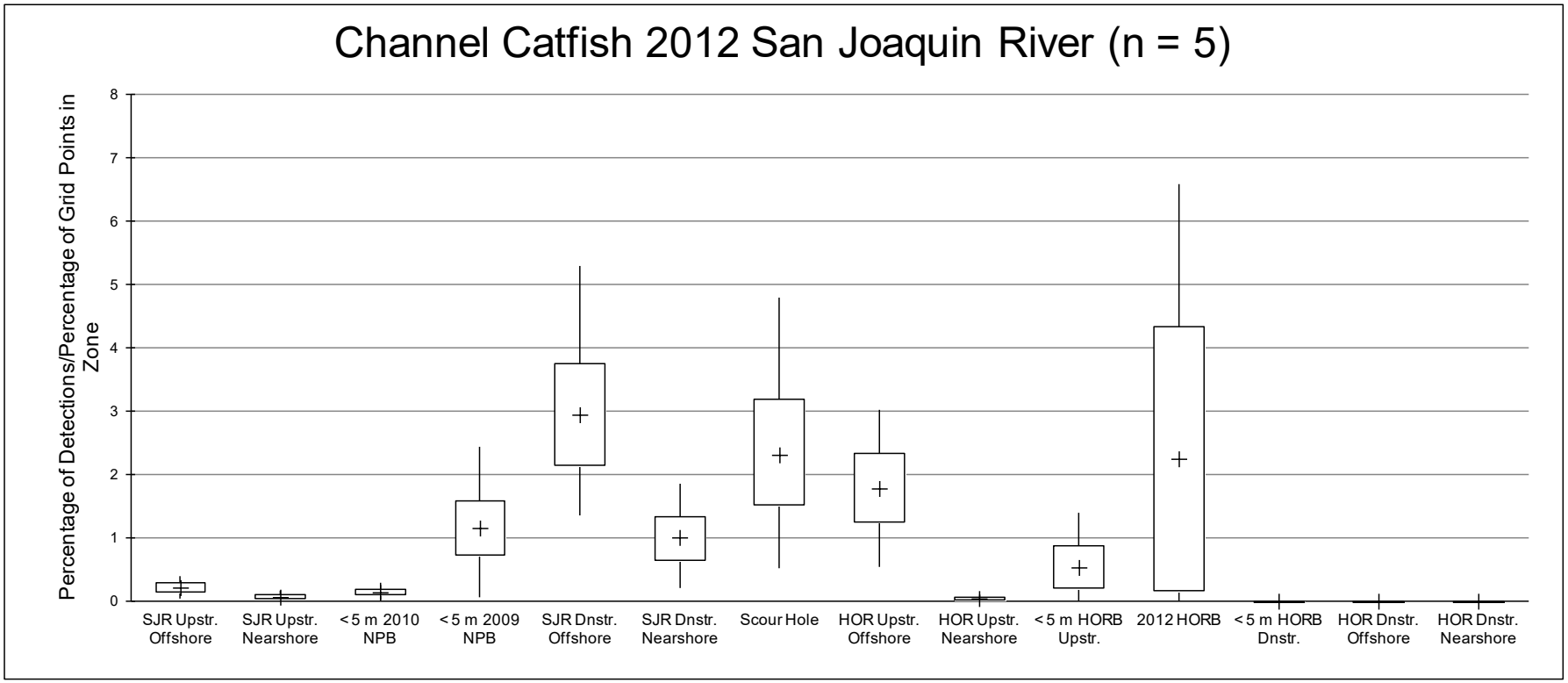
Three largemouth bass released into HOR downstream of the 2012 physical rock barrier were detected most frequently within the footprint of the physical rock barrier bottom (bootstrapped mean: 32%, 95% confidence interval: 13 to 72%) or within 5 m of the barrier (bootstrapped mean: 27%, 95% confidence interval: 10 to 58%) (Figure 6-17). The small surface area of the wetted portion of the barrier bottom zone, coupled with the relatively large percentage of detections within this zone, led to a high use index (95% confidence interval: 1.2 to 8.0); the HOR study area downstream offshore zone was used infrequently relative to its size (95% confidence interval: 0.13 to 0.77) (Figure 6-18).

The largemouth bass with tag code 4306 was tagged and released in 2009. Approximately 40% of its detections were nearshore in a quite restricted area (zone 11), whereas 46% of its detections were within 5 m of the 2009 non-physical barrier (either nearshore in zone 8, or offshore in zones 28 and 29) (Table 6-65).

Striped Bass

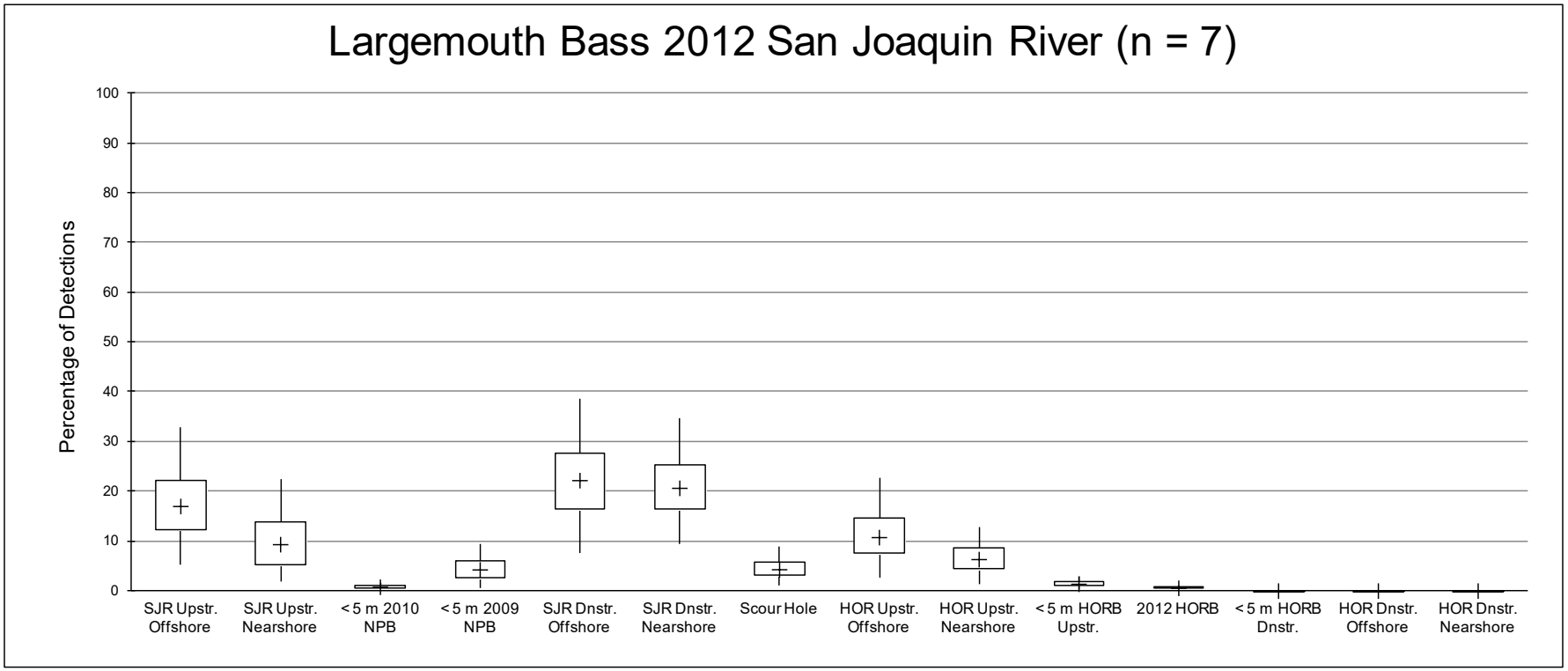
Striped bass tagged and released in 2011 (n = 10) were detected most frequently in offshore areas (San Joaquin River upstream offshore and HOR upstream offshore), as well as the scour hole; there was a bootstrapped mean of approximately 20% of detections in these zones (Figure 6-19). Note that the acoustic array's detection ability was somewhat limited in the HOR study area zones in 2011. As a result, the HOR zones downstream of the 2012 physical rock barrier bottom zones would not have registered detections (and were excluded from the calculations of use relative to zone size).

There was considerable variability in the percentage of detections in each zone relative to zone size. Detections within 5 m of the 2009 non-physical barrier alignment were relatively frequent relative to the small size of this zone (95% confidence interval: 0.9 to 3.1); this was also the case for the scour hole (95% confidence interval: 0.7 to 4.1) (Figure 6-20). Relative to zone size, there was low use of the San Joaquin River upstream offshore and San Joaquin River downstream nearshore zones by striped bass in 2011.



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

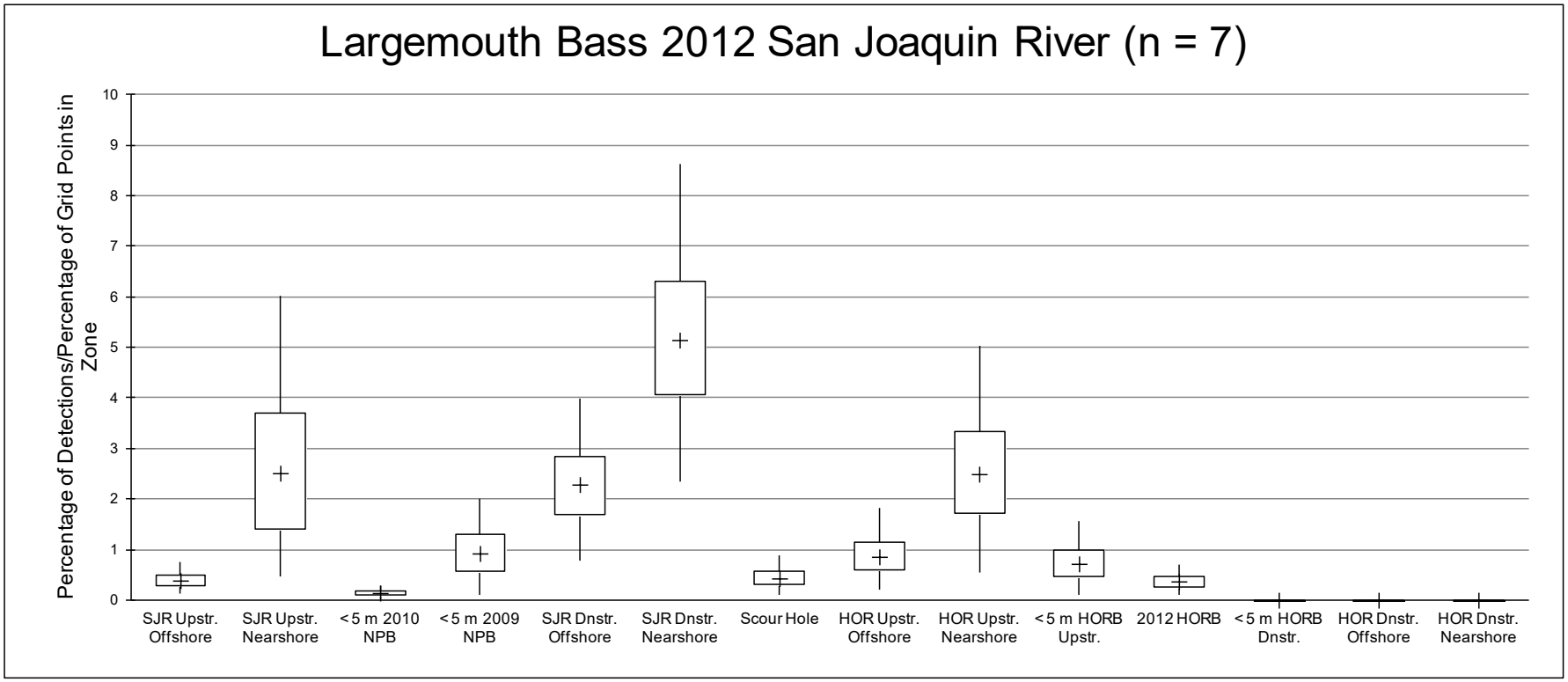
Figure 6-14 **Percentage of Tag Detections for Channel Catfish within Different Zones of the HOR Study Area, Divided by Percentage of Grid Points in Each Zone for 2012 San Joaquin River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream

Source: Present study

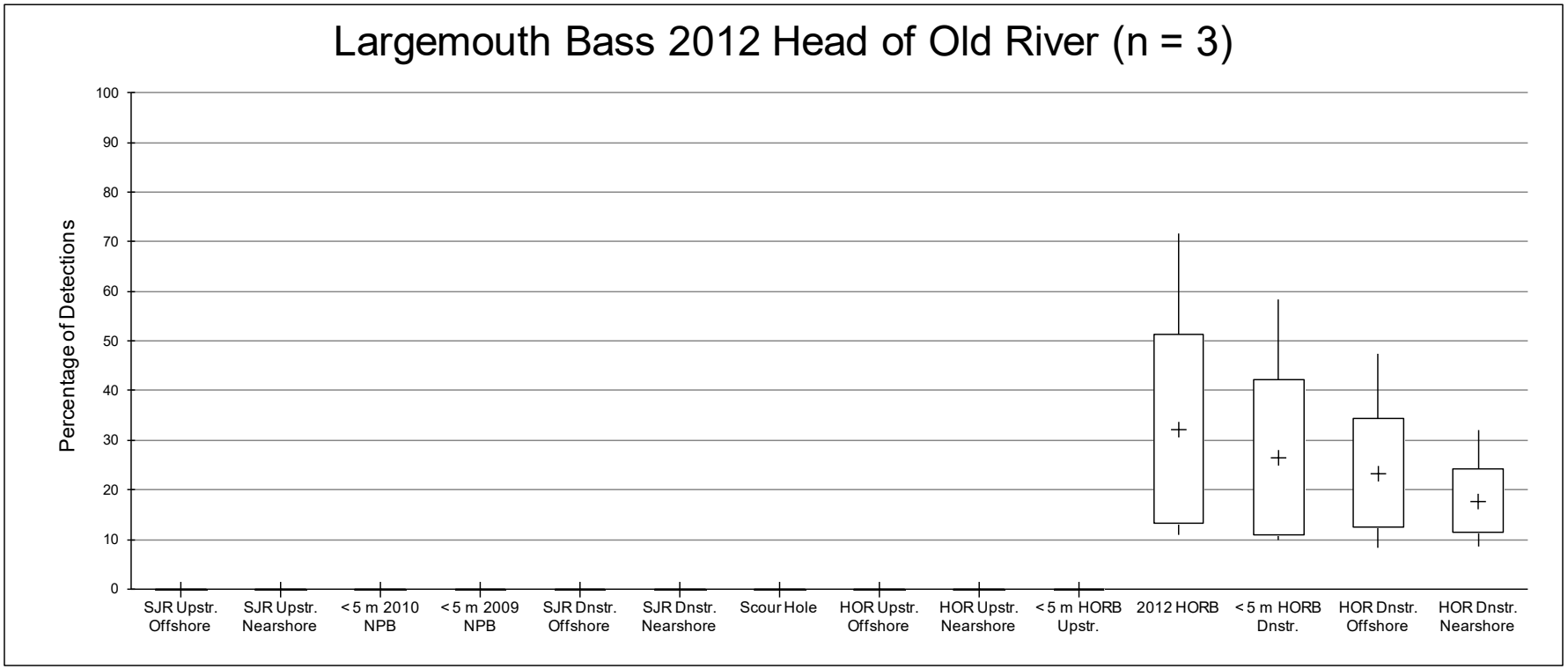
Figure 6-15 **Percentage of Tag Detections for Largemouth Bass within Different Zones of the HOR Study Area for 2012 San Joaquin River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream

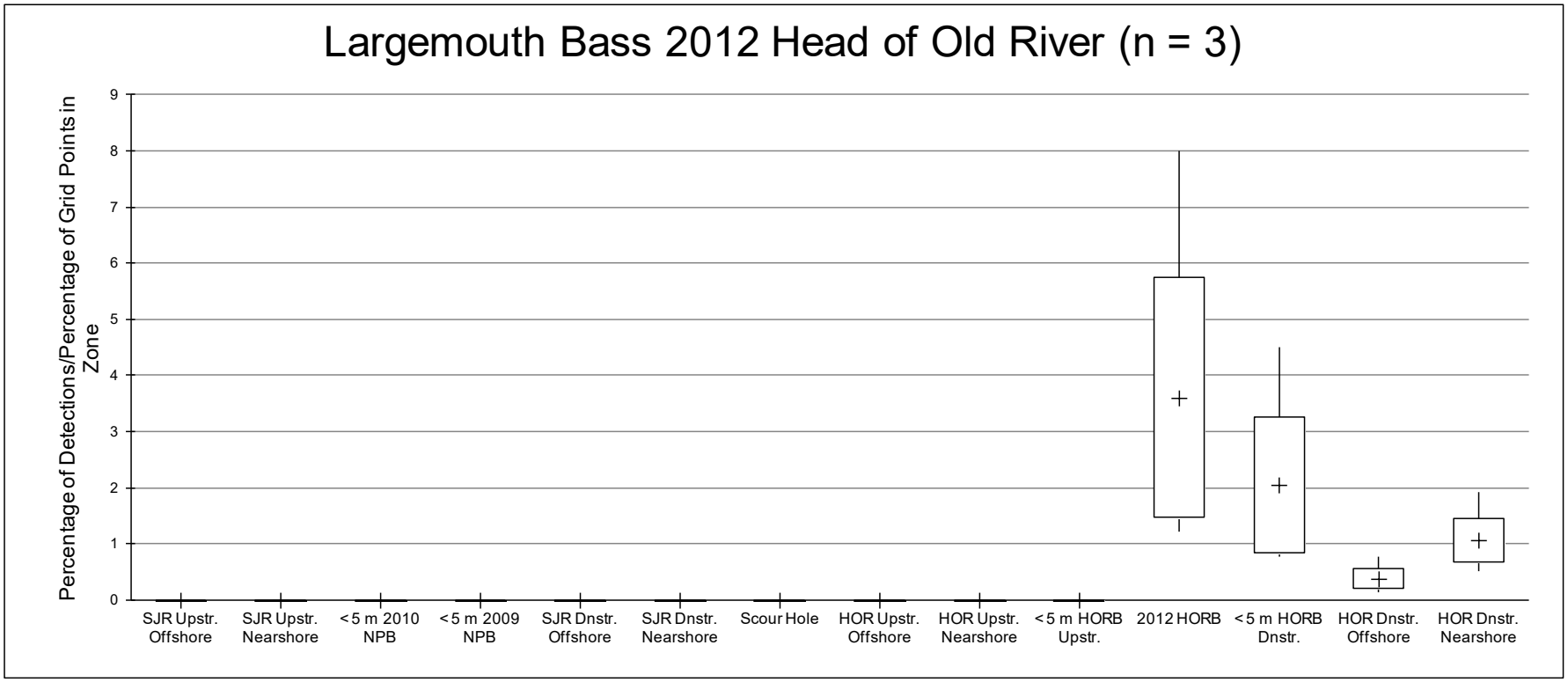
Source: Present study

Figure 6-16 **Percentage of Tag Detections for Largemouth Bass within Different Zones of the HOR Study Area, Divided by Percentage of Grid Points in Each Zone for 2012 San Joaquin River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



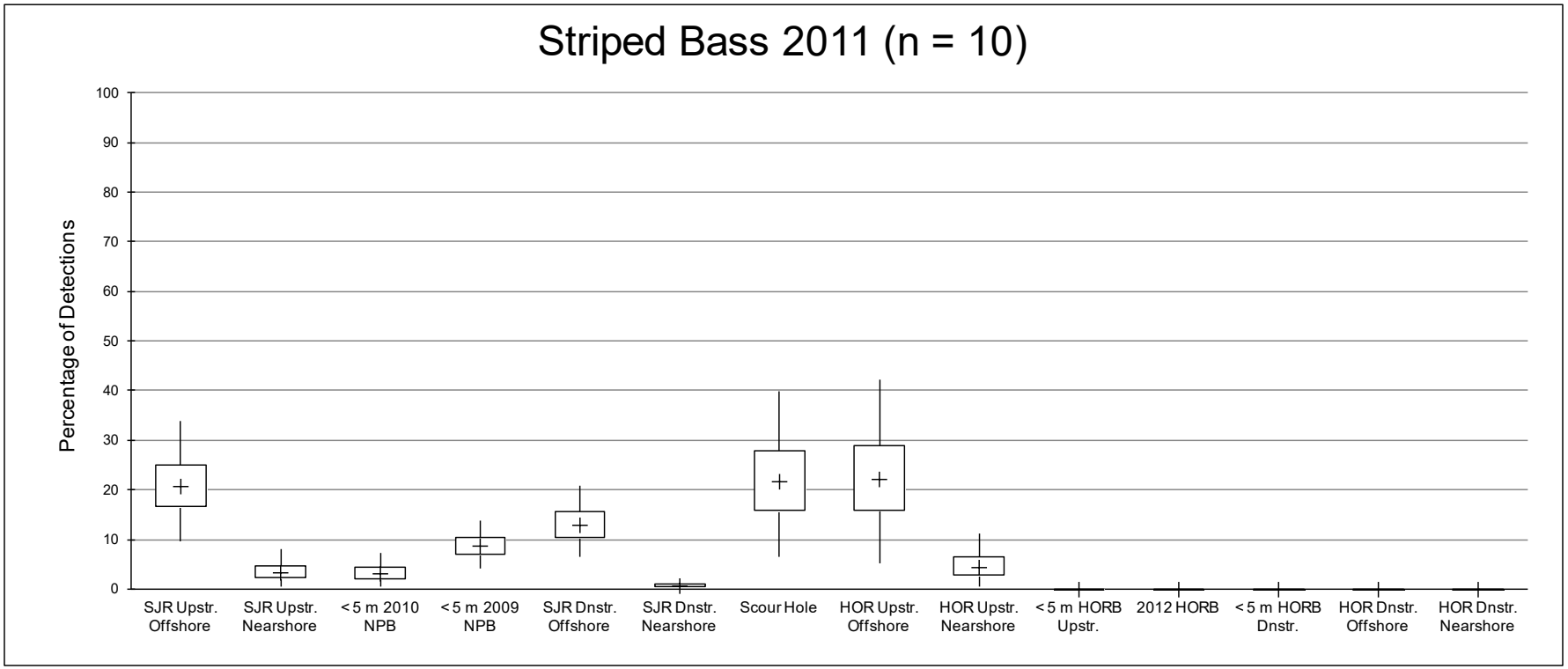
Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

Figure 6-17 **Percentage of Tag Detections for Largemouth Bass within Different Zones of the HOR Study Area for 2012 Head of Old River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

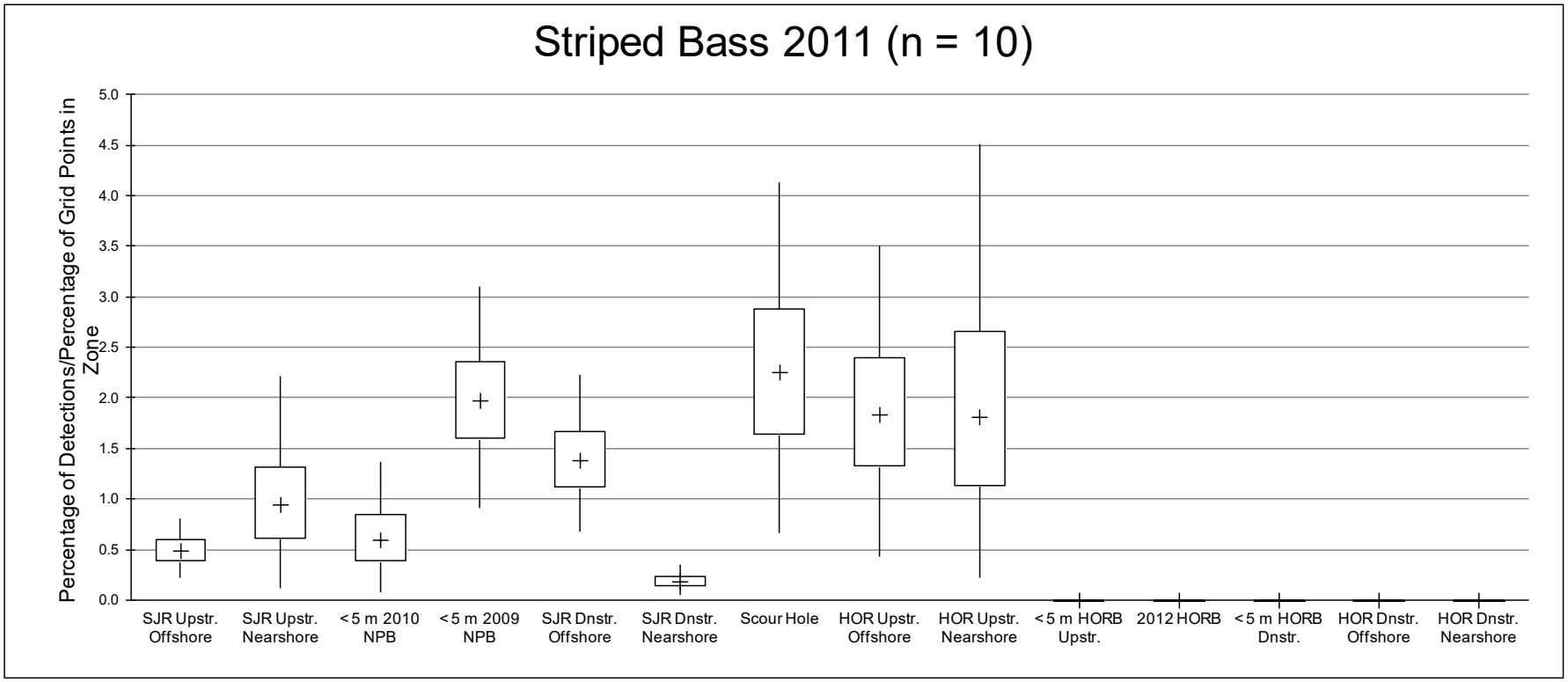
Figure 6-18 **Percentage of Tag Detections for Largemouth Bass within Different Zones of the HOR Study Area, Divided by Percentage of Grid Points in Each Zone for 2012 Head of Old River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

Figure 6-19

Percentage of Tag Detections for Striped Bass within Different Zones of the HOR Study Area for 2011 Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

Figure 6-20 Percentage of Acoustic Tag Detections for Striped Bass within Different Zones of the HOR Study Area, Divided by Percentage of Grid Points in Each Zone for 2011 Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)

Striped bass released in the San Joaquin River in 2012 (n = 4) had the highest frequency of detection in the San Joaquin River downstream offshore zone (bootstrapped mean: 41%, 95% confidence interval: 16 to 70%) (Figure 6-21). The percentage of detections relative to zone size also was high for this zone (95% confidence interval: 4.2 to 7.2) (Figure 6-22). Most of the other zones upstream of the divergence and in the upstream HOR study area were used considerably less, both relative to their size and in absolute terms.

Five striped bass released into HOR downstream of the physical rock barrier in 2012 were most frequently detected offshore in the HOR study area downstream of the physical rock barrier (HOR study area downstream offshore; bootstrapped mean: 66%, 95% confidence interval: 40 to 90%) and less frequently near the physical rock barrier or nearshore (Figure 6-23). Relative to zone size, there was less difference in use of the zones than when comparing the percentage of detections alone (Figure 6-24).

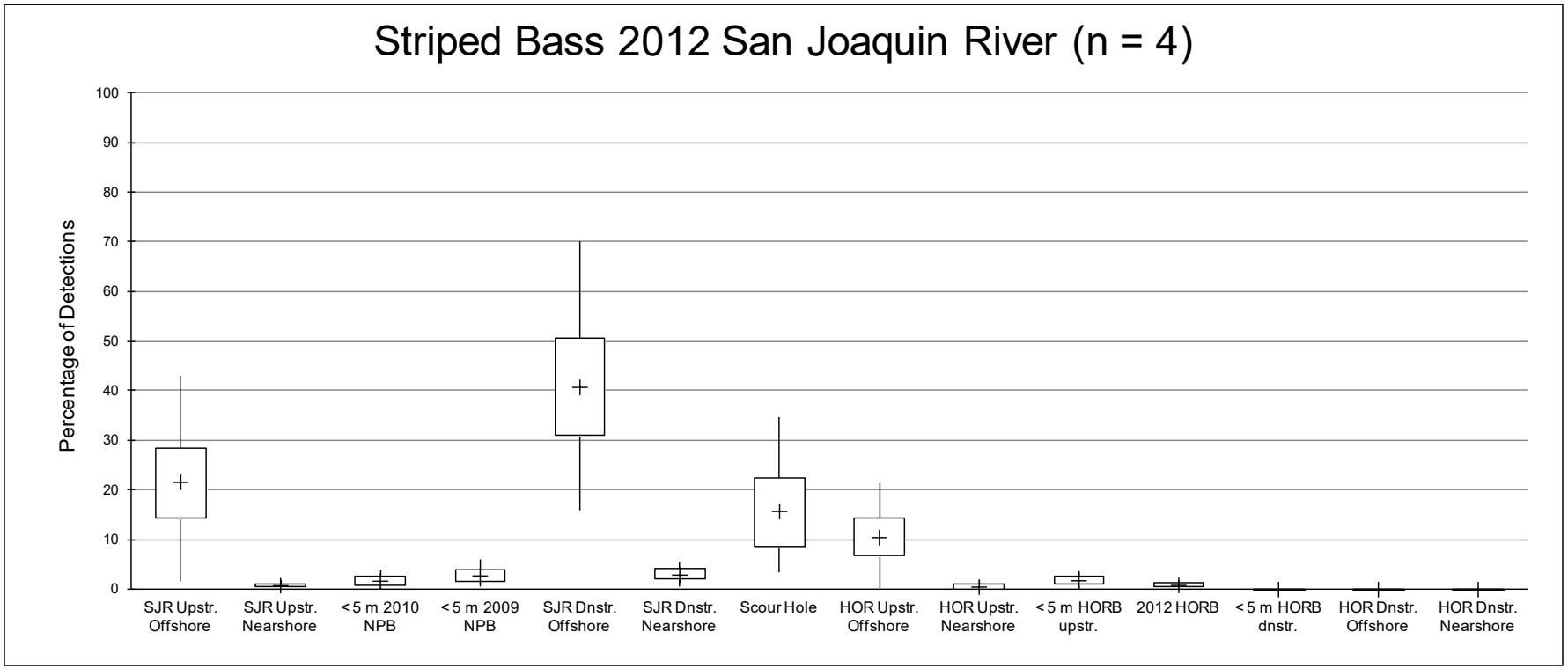
In addition to the striped bass included in the foregoing analyses, two striped bass (tag codes 2024 and 2472) were tagged and released in 2010. These fish each had more than 1,000 detections (Table 6-65) and were detected at the HOR study area for 0.6 to 3 hours (Table 6-64). Of interest is the extent to which they were found near the 2010 non-physical barrier. The acoustic tag detection data suggest that they spent a small proportion (1% or less) of their time within 5 m of the non-physical barrier (Table 6-65). Other striped bass tagged and released in 2009 and 2010 (tag codes 2976 and 4222) were present in the study area for short durations (0.3 to 0.5 hours). Striped bass 2976 spent approximately 20% of its time within 5 m of the 2010 non-physical barrier, whereas striped bass 4222 was not detected within 5 m of the 2009 non-physical barrier (Table 6-65).

White Catfish

White catfish tagged and released in 2011 spent a considerable percentage of their time at the scour hole (bootstrapped mean: 69%, 95% confidence interval: 26–99%) (Figure 6-25). Three individuals (tag codes 3352, 3394, and 3408) that were captured, tagged, and released at the scour hole subsequently remained almost entirely within that area; one individual (tag code 2346) was caught and released in the San Joaquin River upstream of the divergence, and only 2% of its detections were at the scour hole, with the final detection suggesting emigration down Old River. The percentage of detections for white catfish at the scour hole was high relative to the size of this zone (Figure 6-26).

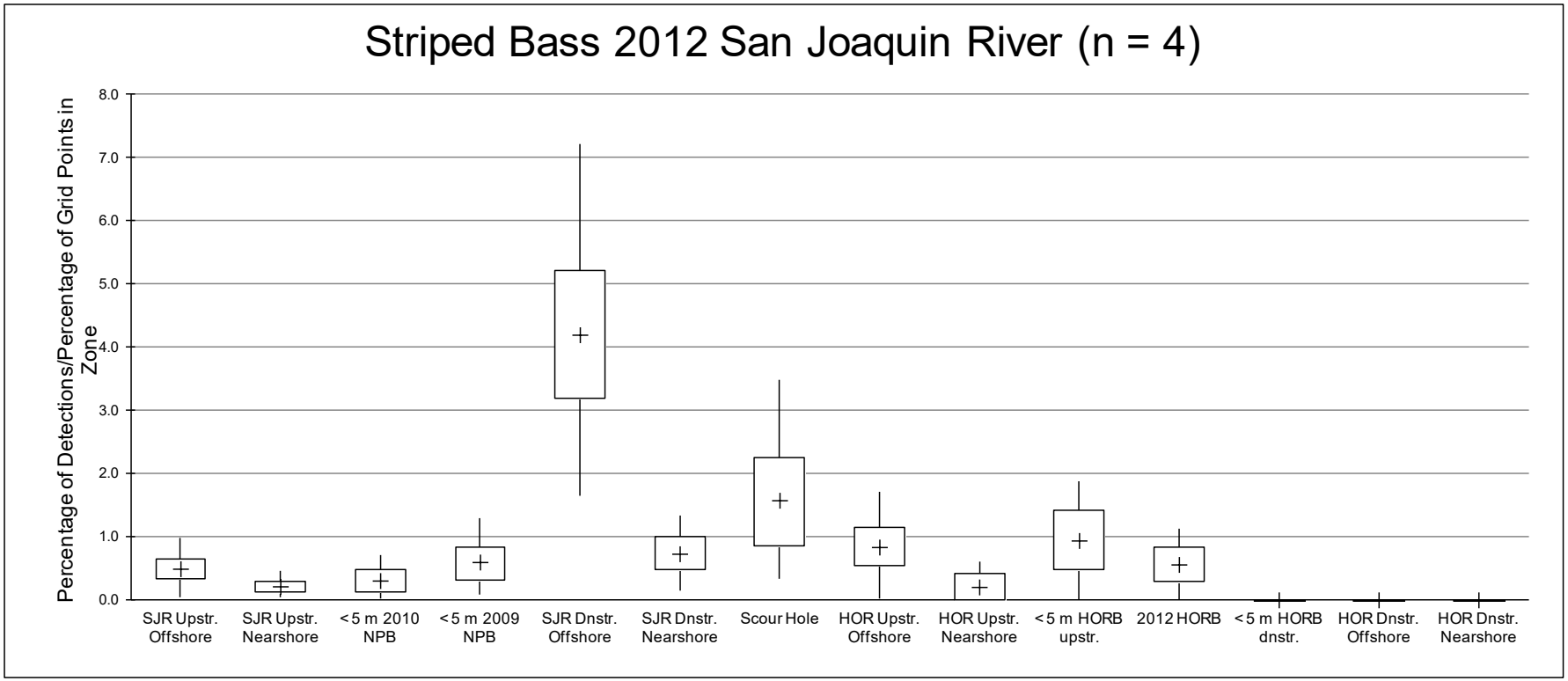
Velocity

The estimated near-surface velocities at the portions of the HOR study area occupied by tagged predatory fish generally were quite different from all of the available velocities at the overall HOR study area upstream of the physical rock barrier (Table 6-66). Channel catfish, largemouth bass, and white catfish all had median detection velocities that were considerably lower than the overall median velocities present in the study area. Striped bass detection velocity was variable in relation to all available velocities.



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

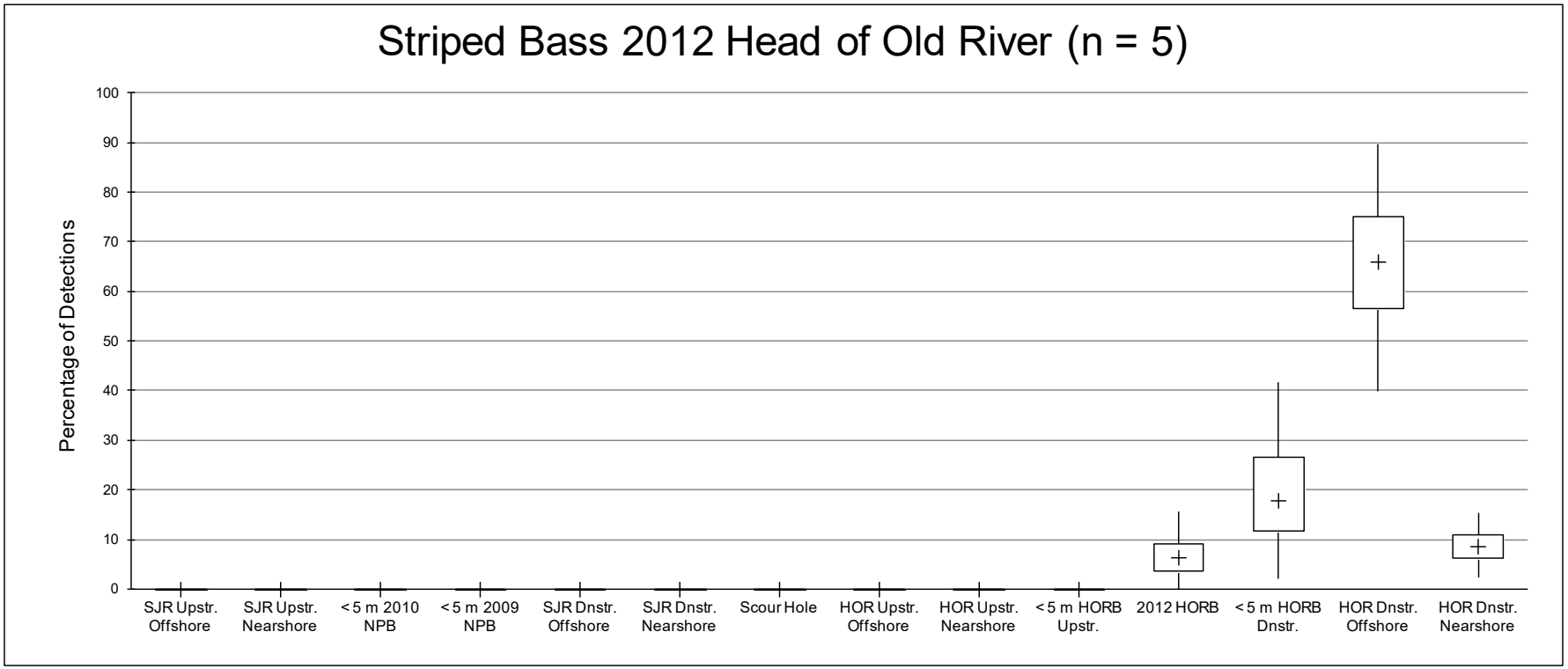
Figure 6-21 **Percentage of Tag Detections for Striped Bass within Different Zones of the HOR Study Area, for 2012 San Joaquin River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

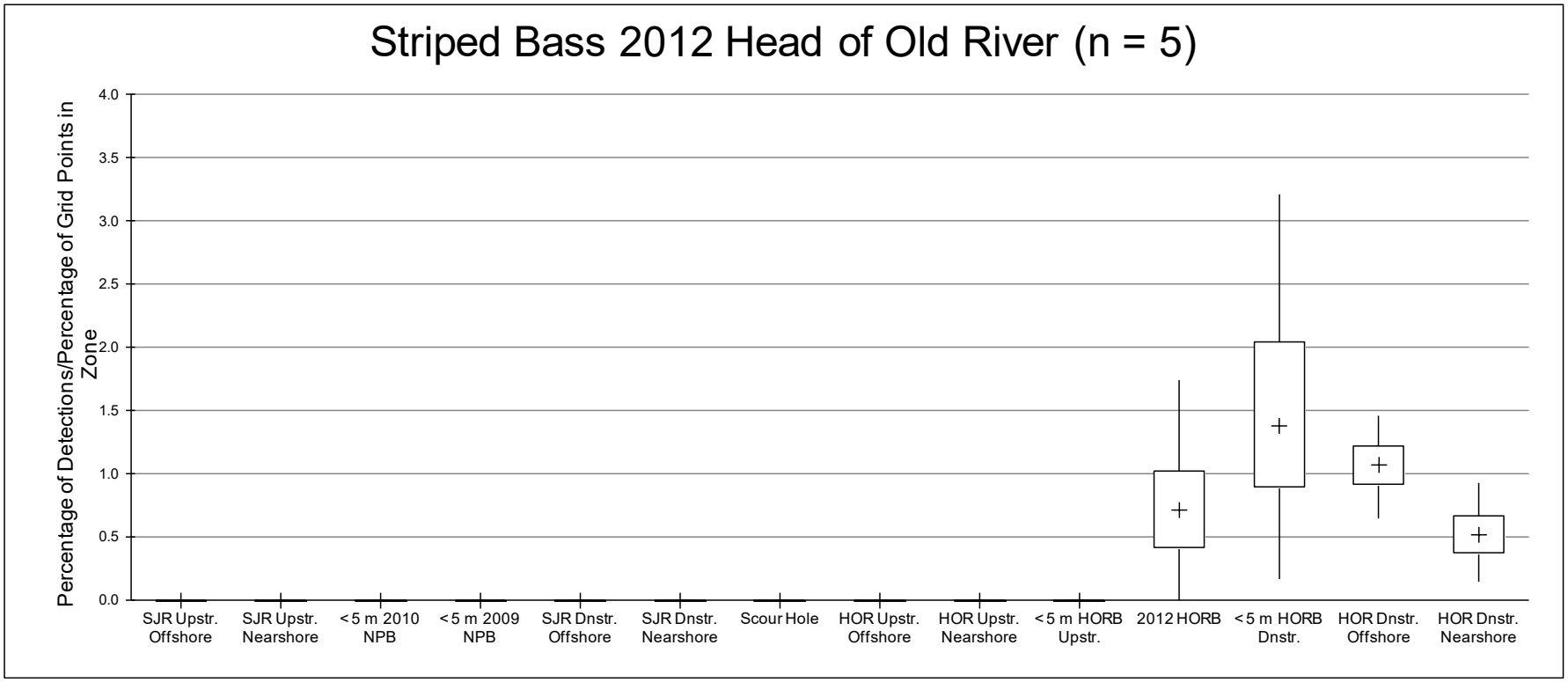
Figure 6-22

Percentage of Tag Detections for Striped Bass within Different Zones of the HOR Study Area, Divided by Percentage of Grid Points in Each Zone for 2012 San Joaquin River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

Figure 6-23 **Percentage of Tag Detections for Striped Bass within Different Zones of the HOR Study Area for 2012 Head of Old River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**

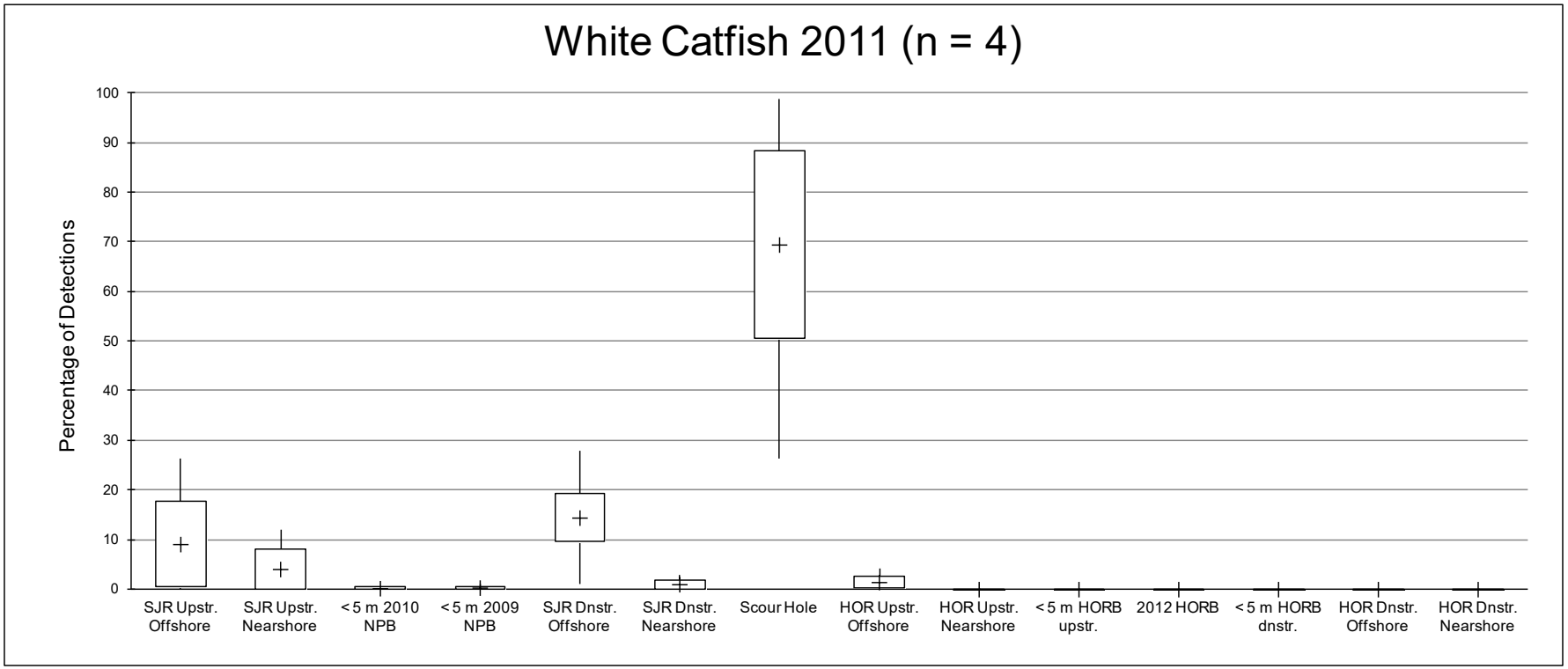


Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream

Source: Present study

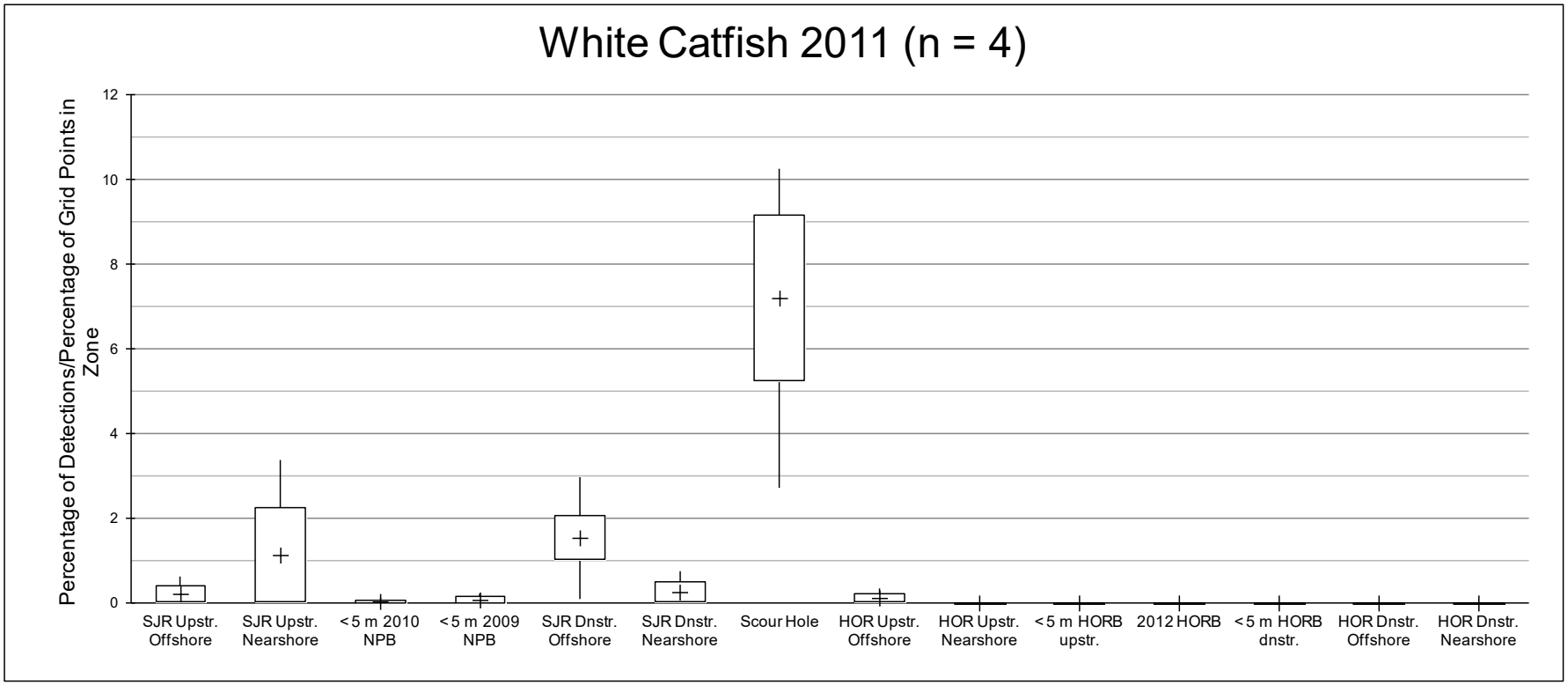
Figure 6-24

Percentage of Tag Detections for Striped Bass within Different Zones of the HOR Study Area, Divided by Percentage of Grid Points in Each Zone for 2012 Head of Old River Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream
Source: Present study

Figure 6-25 **Percentage of Tag Detections for White Catfish within Different Zones of the HOR Study Area for 2011 Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Physical Rock Barrier; NPB = non-physical barrier (BAFF); SJR = San Joaquin River; Upstr. = upstream

Source: Present study

Figure 6-26

Percentage of Tag Detections for White Catfish within Different Zones of the HOR Study Area, Divided by Percentage of Grid Points in Each Zone for 2011 Releases: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)

Table 6-66
Summary of Estimated Median Near-Surface Velocity and Percentage of Observations in Areas in which Tagged Predatory Fish Were Detected, Relative to All Available Velocities at the Head of Old River Study Area, Upstream of the 2012 Physical Rock Barrier

Species	Tag Code	Available Velocities (All) or at which Fish Detected	No. of Observations	Median Velocity (m/s)	Percentage of Observations by Velocity (roundest to nearest 0.05 m/s)												
					0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6
Channel Catfish	2490	All	7,425,516	0.15	16	19	9	10	14	15	9	7	0	0	0	0	0
	2490	Detected	9,120	0.03	31	61	5	2	1	0	0	0	0	0	0	0	0
Channel Catfish	2763	All	77,864,150	0.11	18	22	15	15	13	11	5	2	0	0	0	0	0
	2763	Detected	66,018	0.05	35	42	16	7	1	0	0	0	0	0	0	0	0
Channel Catfish	2847	All	4,842,761	0.23	13	18	8	6	5	6	9	14	18	2	0	0	0
	2847	Detected	3,969	0.11	4	27	23	19	10	12	2	2	0	0	0	0	0
Channel Catfish	2952	All	13,180,062	0.11	17	21	15	18	15	8	4	1	0	0	0	0	0
	2952	Detected	16,417	0.03	28	57	5	4	5	1	0	0	0	0	0	0	0
Channel Catfish	2994	All	4,273,563	0.12	18	20	13	17	17	12	1	0	0	0	0	0	0
	2994	Detected	3,761	0.03	49	28	12	11	1	0	0	0	0	0	0	0	0
Largemouth Bass	2028	All	98,542,213	0.10	17	23	16	12	12	11	7	2	0	0	0	0	0
	2028	Detected	114,293	0.02	61	39	0	0	0	0	0	0	0	0	0	0	0
Largemouth Bass	2070	All	3,699,787	0.09	18	25	18	7	8	12	10	2	0	0	0	0	0
	2070	Detected	2,997	0.01	72	25	3	0	0	0	0	0	0	0	0	0	0
Largemouth Bass	2259	All	58,911,993	0.11	17	23	15	12	12	11	8	3	0	0	0	0	0
	2259	Detected	68,472	0.03	47	51	1	0	0	0	0	0	0	0	0	0	0
Largemouth Bass	2280	All	3,782,191	0.15	16	19	10	13	18	15	5	4	0	0	0	0	0
	2280	Detected	398	0.03	38	31	5	2	6	0	0	12	6	0	0	0	0
Largemouth Bass	2532	All	49,136,437	0.11	17	22	15	16	15	11	4	0	0	0	0	0	0
	2532	Detected	39,305	0.02	81	19	1	0	0	0	0	0	0	0	0	0	0
Largemouth Bass	2721	All	207,541,341	0.11	17	21	15	14	13	11	6	2	0	0	0	0	0
	2721	Detected	207,818	0.02	50	46	3	0	0	0	0	0	0	0	0	0	0
Largemouth Bass	3078	All	92,546,559	0.12	17	21	14	10	11	12	10	4	0	0	0	0	0
	3078	Detected	32,571	0.03	48	48	3	0	0	0	0	0	0	0	0	0	0

Table 6-66
Summary of Estimated Median Near-Surface Velocity and Percentage of Observations in Areas in which Tagged Predatory Fish Were Detected, Relative to All Available Velocities at the Head of Old River Study Area, Upstream of the 2012 Physical Rock Barrier

Species	Tag Code	Available Velocities (All) or at which Fish Detected	No. of Observations	Median Velocity (m/s)	Percentage of Observations by Velocity (roundest to nearest 0.05 m/s)												
					0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6
Striped Bass	2007	All	1,165,101	0.21	10	16	11	7	6	9	16	12	11	0	0	0	0
	2007	Detected	1,058	0.16	5	23	20	15	6	17	8	5	1	0	0	0	0
Striped Bass	2154	All	470,252,923	0.12	16	21	14	12	12	11	8	4	2	0	0	0	0
	2154	Detected	566,232	0.16	1	9	20	27	21	12	6	3	2	1	0	0	0
Striped Bass	2343	All	64,892,387	0.10	17	24	18	13	11	9	5	2	0	0	0	0	0
	2343	Detected	75,883	0.04	28	41	17	9	5	1	0	0	0	0	0	0	0
Striped Bass	2700	All	1,135,344	0.20	14	18	8	6	7	13	21	11	1	0	0	0	0
	2700	Detected	780	0.36	0	0	0	0	0	0	22	29	47	2	0	0	0
White Catfish	2931	All	1,910,552	0.20	11	17	10	7	7	11	16	19	2	0	0	0	0
	2931	Detected	2,192	0.00	85	13	1	0	1	0	0	0	0	0	0	0	0

Notes: m/s = meters per second; No. = number
Source: Present study

Channel Catfish

The median detection velocity for channel catfish ranged from 0.03 m/s (tag codes 2490, 2952, and 2994) to 0.11 m/s (tag code 2847), compared with median available velocities of 0.11 to 0.23 m/s (Table 6-66). A generally large percentage (approximately 75% or more) of tag detections was estimated to occur in areas with near-surface velocity less than 0.075 m/s (the exception was tag code 2847); by contrast, only 35 to 40% of available velocities were in this range. This was reflected in the index of detection velocity to available velocity, which generally was well above 1 (Figure 6-27), while the 95% confidence intervals for velocity of 0.075 to 0.275 m/s overlapped 1, indicating that this range of velocity was used more in proportion to its availability; higher velocity (>0.275 m/s) was rarely used (Table 6-66; Figure 6-27).

Largemouth Bass

The median detection velocity for largemouth bass ranged from 0.01 m/s (tag code 2070) to 0.03 m/s (tag codes 2259, 2280, and 3078), compared with median available velocities of 0.09 to 0.15 m/s (Table 6-66). For most tagged largemouth bass, nearly all (96% to 100%) of tag detections were estimated to be in areas with near-surface velocity less than 0.075 m/s. The exception was tag code 2280 (70% of detections in this range), and this individual was detected relatively rarely during the period for which velocity was modeled. By contrast, approximately 38–44% of all available velocities were less than 0.075 m/s.

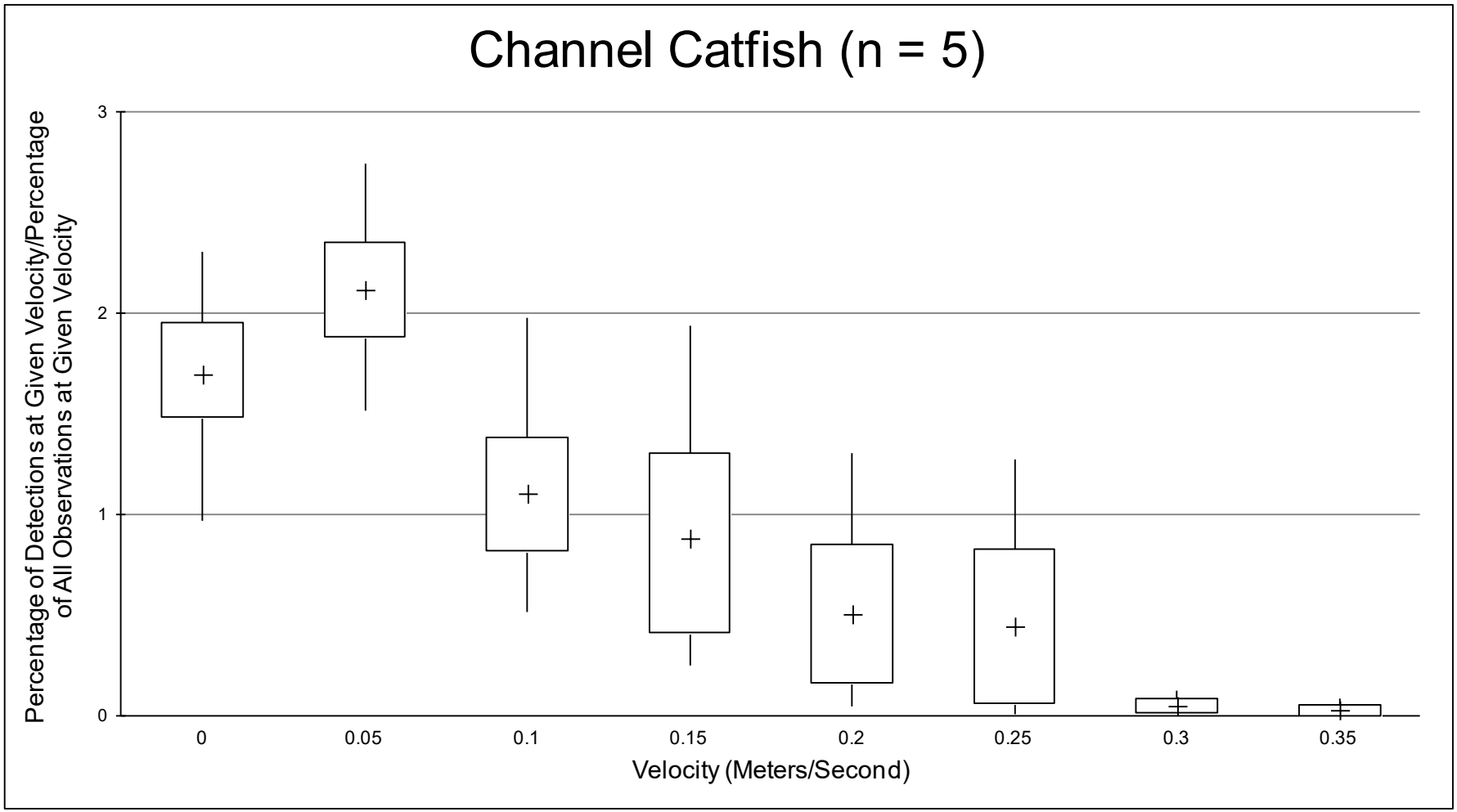
Occupation of lower-velocity areas was reflected in the index of detection velocity to available velocity, for which the 95% confidence intervals were considerably above 1, indicating greater use than proportionally available (Figure 6-28). By contrast, the 95% confidence intervals for velocity indices over the range of 0.075 to 0.325 m/s were below 1, indicating that this range of velocity was used considerably less than its proportional availability. Overlap of the 95% confidence intervals of velocity from 0.325 to 0.425 m/s with a velocity use index of 1 reflects the single individual (tag code 2280) that was detected relatively rarely.

Striped Bass

Four acoustically tagged striped bass met the criterion for inclusion in the velocity analysis, 1,000 or more detections before merging with velocity modeling estimates. (Note that the number of detections remaining after the merge with velocity data was lower than 1,000 for some fish [e.g., striped bass tag code 2700] because not all detections were within the grid of velocity estimates or occurred outside the period of velocity data availability.)

The median detection velocity was appreciably greater for striped bass than for the other species (0.16 to 0.34 m/s) for three individuals (tag codes 2007, 2154, and 2700), and similar (0.04 m/s) for the other individual (tag code 2343) (Table 6-66). The median detection velocity for striped bass tag code 2007 (0.16 m/s) was similar to the median of all available velocities (0.21 m/s); the median detection velocities for striped bass tag codes 2154 and 2700 were greater than the median of all available velocities; and the median detection velocity of striped bass 2343 was considerably less than the median of all available velocities (0.04 vs. 0.20 m/s).

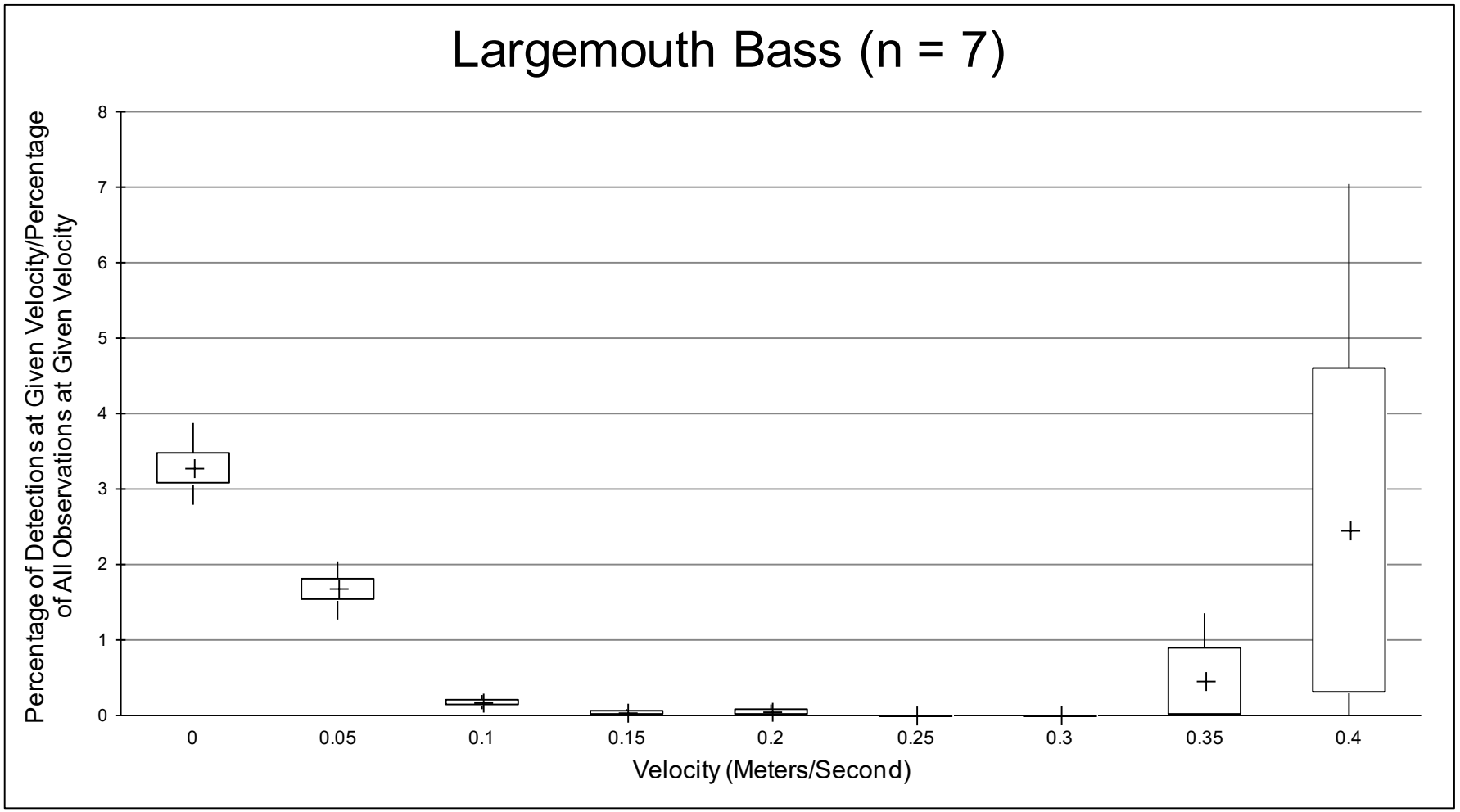
The approximate velocity ranges in which tag detections occurred most frequently differed by fish: 0.025 to 0.275 m/s (tag code 2007), 0.075 to 0.275 m/s (tag code 2154), 0 to 0.125 m/s (tag code 2343), and 0.275 to 0.425 m/s (tag code 2700). This led to little evidence of occupation by fish of any particular velocity in greater or less proportion than it was available in the study area, as judged by the 95% confidence intervals of the velocity index across most velocity increments overlapping an index value of 1 (Figure 6-29).



Note: Velocity is rounded to the nearest 0.05 meter per second.

Source: Present study

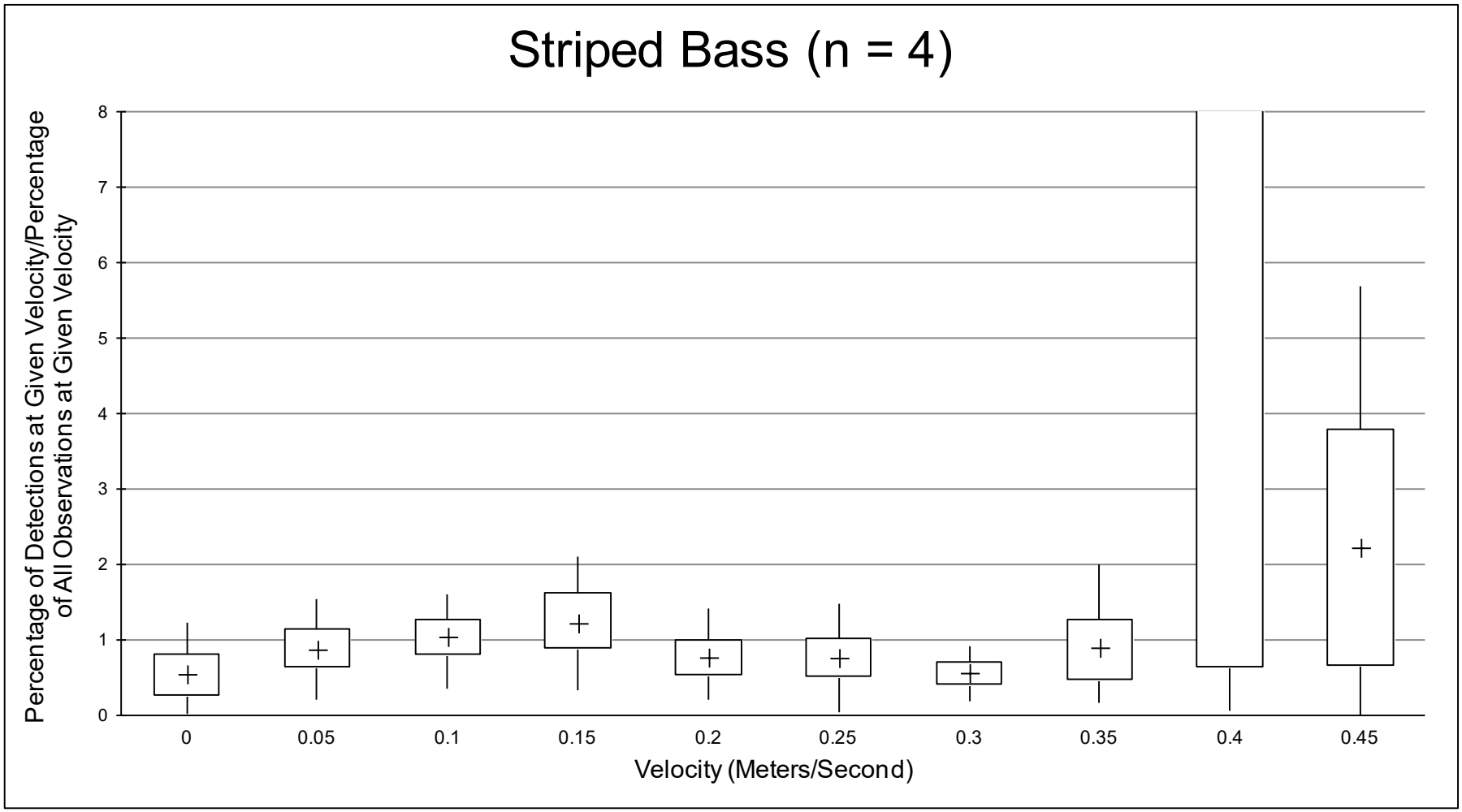
Figure 6-27 **Percentage of Tag Detections for Channel Catfish at Different Near-Surface Velocities at the HOR Study Area, Divided by Percentage of All Near-Surface Velocities in the HOR Study Area, Upstream of the 2012 Physical Rock Barrier: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Note: Velocity is rounded to the nearest 0.05 meter per second.

Source: Present study

Figure 6-28 **Percentage of Tag Detections for Largemouth Bass at Different Near-Surface Velocities at the HOR Study Area, Divided by Percentage of All Near-Surface Velocities in the HOR Study Area, Upstream of the 2012 Physical Rock Barrier: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**



Notes: Velocity is rounded to the nearest 0.05 meter per second. The y-axis of plot is truncated at 8; 95th percentile at 0.4 meters per second was 46.5.
Source: Present study

Figure 6-29 **Percentage of Tag Detections for Striped Bass at Different Near-Surface Velocities at the HOR Study Area, Divided by Percentage of All Near-Surface Velocities in the HOR Study Area, Upstream of the 2012 Physical Rock Barrier: Bootstrapped Mean (+), Interquartile Range (Box), and 95% Confidence Interval (Whiskers)**

White Catfish

The single white catfish (tag code 2931) included in the velocity analysis had a median near-surface detection velocity of 0.00 m/s (Table 6-66), and 97% of its tag detections occurred in areas with velocity of 0.075 m/s or less. This was considerably less than the available velocities at the times of detection (median = 0.20 m/s, 28% of observations less than 0.075 m/s).

Emigration from Study Area

Four of five channel catfish tagged and released into the San Joaquin River in 2012 were last detected within the spatially defined zones of the study area before deactivation of the acoustic array; the last detections suggested that three of the four moved upstream and one moved downstream (Table 6-65). Five of six largemouth bass that were released into and moved out of the study area during the 2009 through 2012 physical rock barrier studies moved downstream. The single largemouth bass tagged and released in 2009 (tag code 4306) was last detected moving downstream into Old River; the single largemouth bass tagged and released in 2011 that appeared to leave the study area (tag code 3436) moved downstream in the San Joaquin River. Three of four largemouth bass tagged and released in the San Joaquin River that left the study area in 2012 moved downstream and one moved upstream.

Of the four striped bass detected in the study area in 2009 and 2010, two appeared to move upstream in the San Joaquin River, one moved downstream in the San Joaquin River, and one moved downstream in Old River, as indicated by the last zones of detections (Table 6-65). There were 29 tagged striped bass for which movement out of the study area could be deduced by the zone of last detection in 2011. Of these, 16 moved downstream in the San Joaquin River, 11 moved downstream in Old River, and two moved upstream in the San Joaquin River. One of six tagged striped bass released into the San Joaquin River in 2012 moved upstream out of the study area, and the remainder moved downstream.

The single white catfish tagged and released in 2011 (tag code 2346) that moved out of the range of detection of the acoustic array was last detected in Old River (i.e., downstream movement) (Table 6-65). The single white catfish tagged and released in the San Joaquin River in 2012 (tag code 2931) moved downstream out of the study area.

STATIONARY TAG LOCATIONS

A total of 24 stationary (i.e., no longer moving, as judged by consistent positions from signals received by hydrophones) salmonid tags were detected at the HOR study area from 2009 through 2012. This finding may indicate predation following these salmonids' entry into the study area as juveniles, and subsequent defecation. In both 2009 and 2010, only a single stationary tag was detected; 16 stationary tags were detected in 2011 (juvenile Chinook salmon, 10; steelhead, 6) and 6 in 2012 (all juvenile Chinook salmon).

The majority of stationary tags (20 of 24; 83%) was detected in the San Joaquin River downstream of the divergence with Old River; of these, a greater percentage was found at the scour hole (12 of 20; 60%) than offshore (8 of 20; 40%) (Figure 6-30). One stationary juvenile Chinook salmon tag was detected immediately adjacent to the downstream side of the physical rock barrier, with another tag approximately 91 m downstream in Old River. The stationary steelhead tag immediately adjacent to the upstream culvert zone of the physical rock barrier was detected in 2011, and therefore, was not associated with the physical rock barrier. No stationary tags were detected within 5 m of shore (Figure 6-30).

To some extent, the differences in the number of stationary tags detected in each year are related to hydrophone placement, as well as to the number of tagged juveniles entering the study area. In 2011, a hydrophone was placed deep within the scour hole, and therefore, allowed better detection of stationary tags in that year, even though tags classified as having been preyed upon were less frequent in that year than other years (see Section 6.2, "Predation on Juvenile Salmonids Including Barrier Effects"). However, the number of tagged juveniles entering the study area in 2011 (approximately 1,200) was considerably greater than in the other years (approximately 270 to 650 per year). These two factors combined resulted in relatively more stationary tags being detected in 2011 than other years.

6.3.2 HYDROACOUSTIC DATA

AREAS OCCUPIED AND DIEL CHANGES IN DEPTH

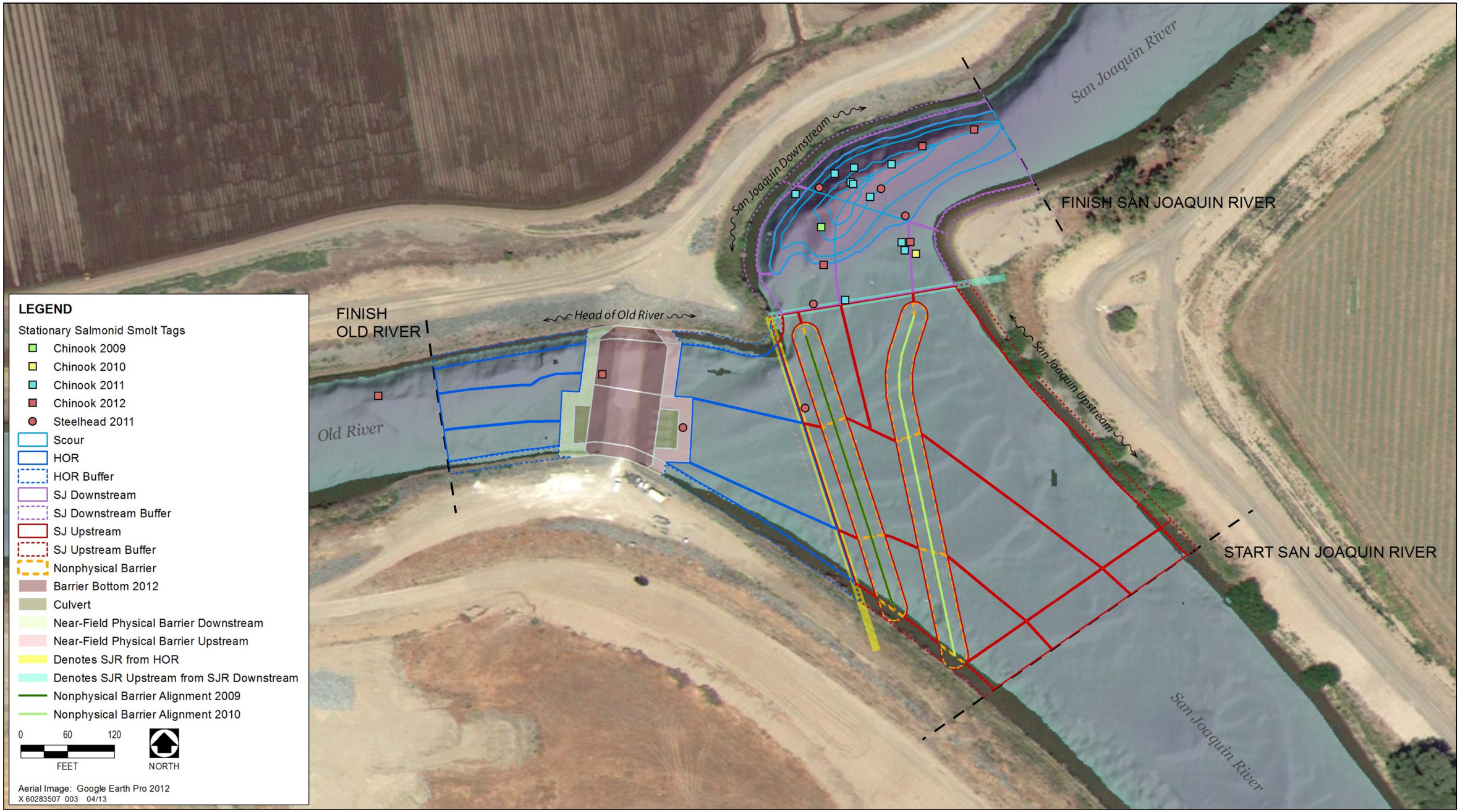
Areas Occupied

A total of 600 fish greater than 30 cm TL were detected within the spatially defined zones of the HOR study area during 49 mobile hydroacoustic surveys in 2011 and 2012. The number of fish detected by down-looking surveys was 20 in 2011 and 279 in 2012, which compared with 57 fish in 2011 and 244 fish in 2012 from side-looking surveys. The greatest proportions of fish detected by down-looking surveys were found in the San Joaquin River downstream of the divergence with Old River (75% of fish in 2011, 99% of fish in 2012) (Figure 6-31; Table 6-67). In particular, many fish were detected at the scour hole (35% of fish in 2011, 95% of fish in 2012). (Note that the ability of mobile hydroacoustic surveys to detect fish in the HOR study area zones was limited following installation of the physical rock barrier in 2012.)

Fish distribution as assessed by side-looking mobile hydroacoustic surveys was more equitable at the HOR study area than the distribution assessed by down-looking surveys, with approximately half of the fish detected in the San Joaquin River downstream of Old River in both 2011 and 2012 (Figure 6-32; Table 6-67). Approximately 23% of fish were detected at the scour hole in both years. An appreciable percentage of fish was detected in the offshore portion of the San Joaquin River upstream of the Old River divergence: 14% in 2011 and 32% in 2012.

Diel Changes in Depth

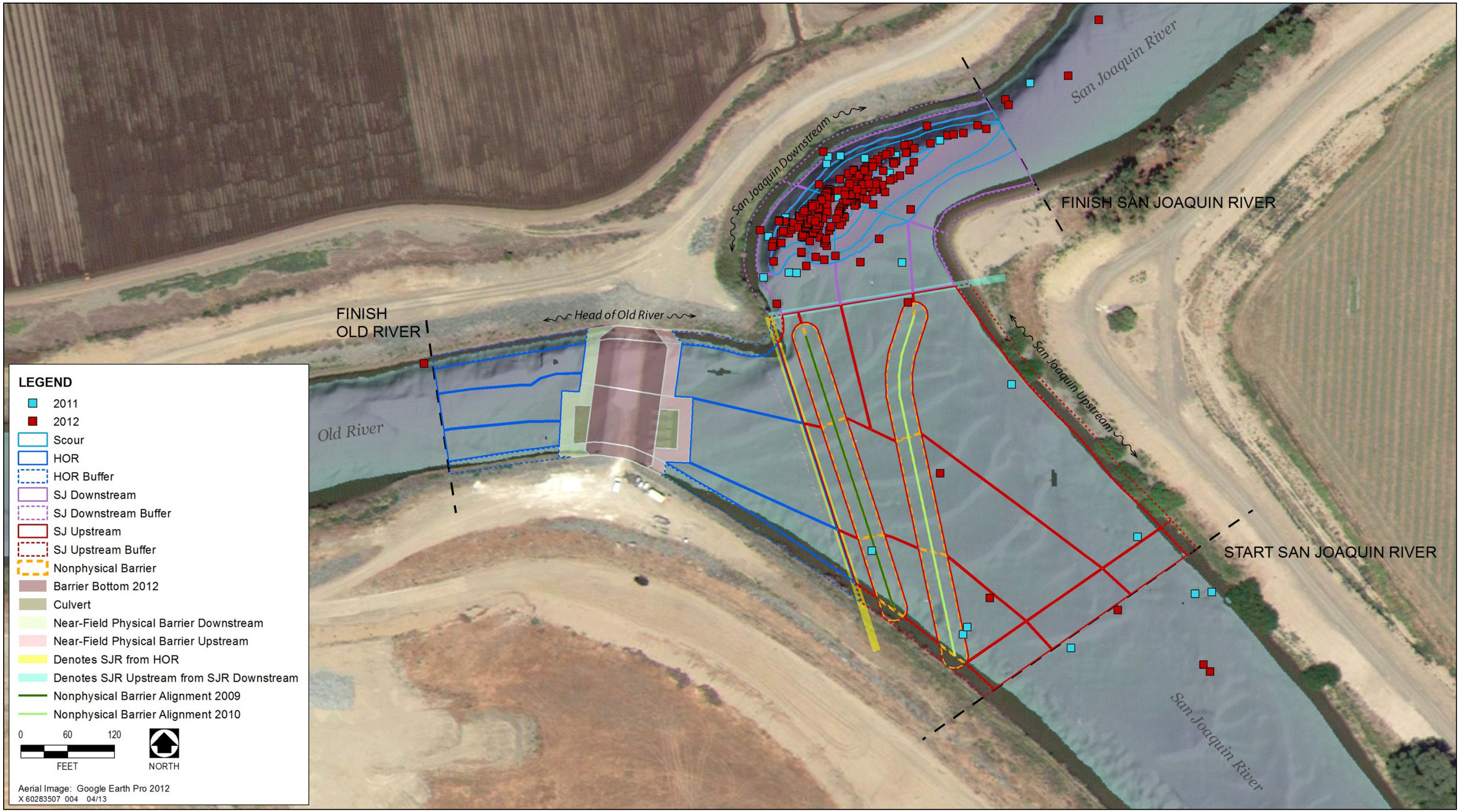
There was little evidence that the depth distribution of fish detected by down-looking mobile hydroacoustic surveys changed in relation to diel period. Figure 6-33 shows the vertical distance from the river bottom, where 23 individual fish were detected (12 during the day, 11 at night), in relation to the total water column (bottom) depth in 2011. Evidence of movement higher into the water column at night would be provided by the black symbols being relatively closer to the dashed water-surface line than the yellow circles for a given bottom depth. No such relationship was apparent. No nighttime were data available from the 2012 sampling, and there was no apparent relationship between diel period (day, dawn, or dusk) and position in the water column for 287 fish (Figure 6-34).



Sources: Google Earth Pro 2012; DWR 2012; Present study

Figure 6-30

Locations of Stationary Juvenile Salmonid Tags, 2009-2012



Sources: Google Earth Pro 2012; DWR 2012; Present study

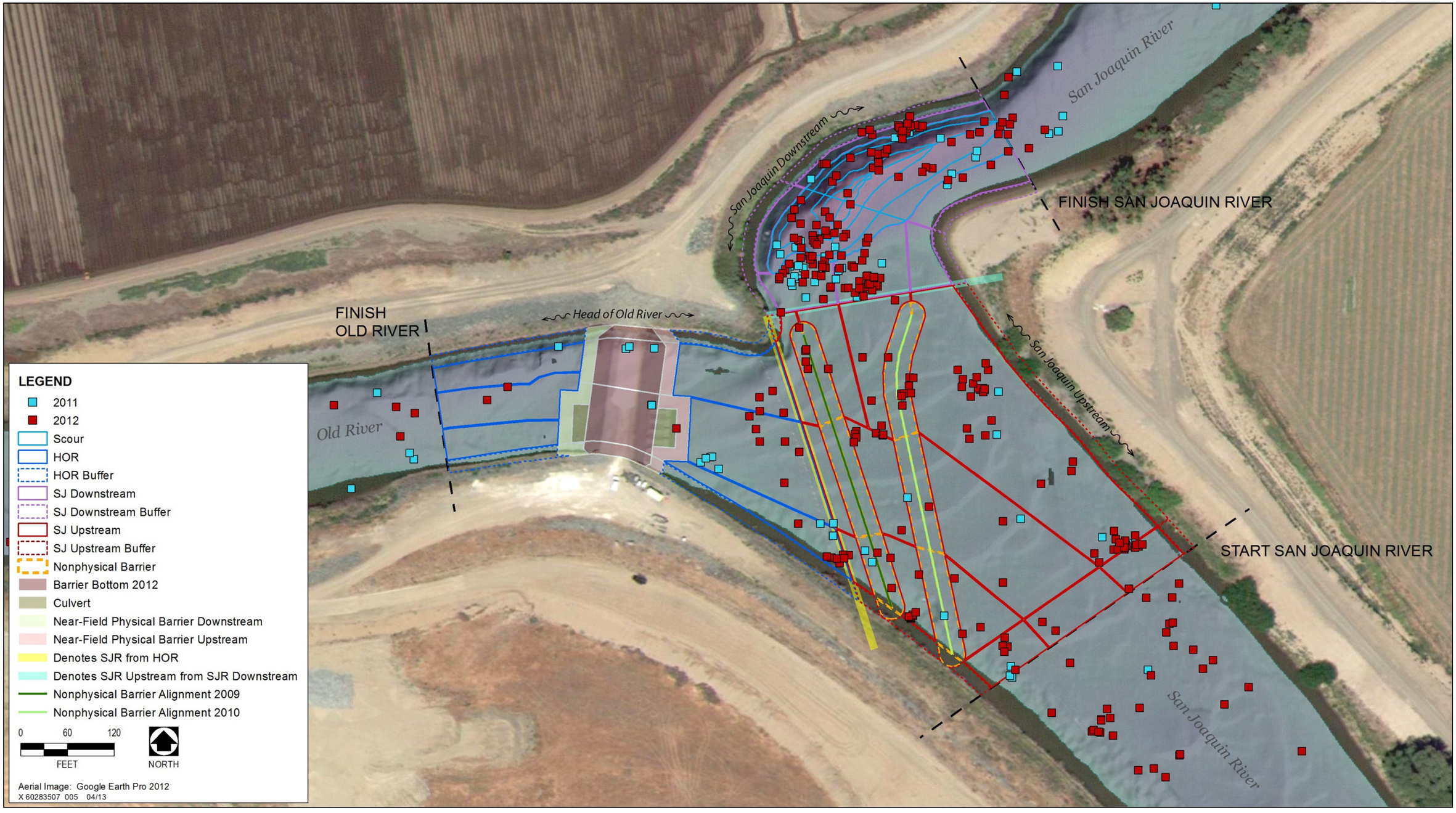
Figure 6-31

Locations of Fish Estimated to be >30 Centimeters Total Length from Down-Looking Mobile Hydroacoustic Surveys, 2011 and 2012

Table 6-67
Number and Percentage of Large Fish >30 Centimeters Total Length Detected by Down- and Side-Looking Mobile Hydroacoustic Surveys in Different Zones at the Head of Old River, 2011 and 2012

Year/Survey Type	SJR Upstr. Offshore	SJR Upstr. Nearshore	<5 m 2010 Nonphysical Barrier	<5 m 2009 Nonphysical Barrier	SJR Dnstr. Offshore	SJR Dnstr. Nearshore	Scour Hole	HOR Upstr. Offshore	HOR Upstr. Nearshore	<5 m HORB Upstr.	2012 HORB	<5 m HORB Dnstr.	HOR Dnstr. Offshore	HOR Dnstr. Nearshore
2011/down	3 (15%)	0 (%)	1 (5%)	1 (5%)	8 (40%)	0 (%)	7 (35%)	0 (%)	0 (%)	0 (%)	0 (%)	0 (%)	0 (%)	0 (%)
2011/side	8 (14%)	0 (%)	2 (4%)	2 (4%)	18 (32%)	0 (%)	13 (23%)	8 (14%)	0 (%)	0 (%)	5 (9%)	0 (%)	1 (2%)	0 (%)
2012/down	3 (1%)	0 (%)	0 (%)	0 (%)	9 (3%)	3 (1%)	264 (95%)	0 (%)	0 (%)	0 (%)	0 (%)	0 (%)	0 (%)	0 (%)
2012/side	79 (32%)	0 (%)	8 (3%)	7 (3%)	69 (28%)	4 (2%)	57 (23%)	17 (7%)	0 (%)	1 (%)	0 (%)	0 (%)	2 (1%)	0 (%)

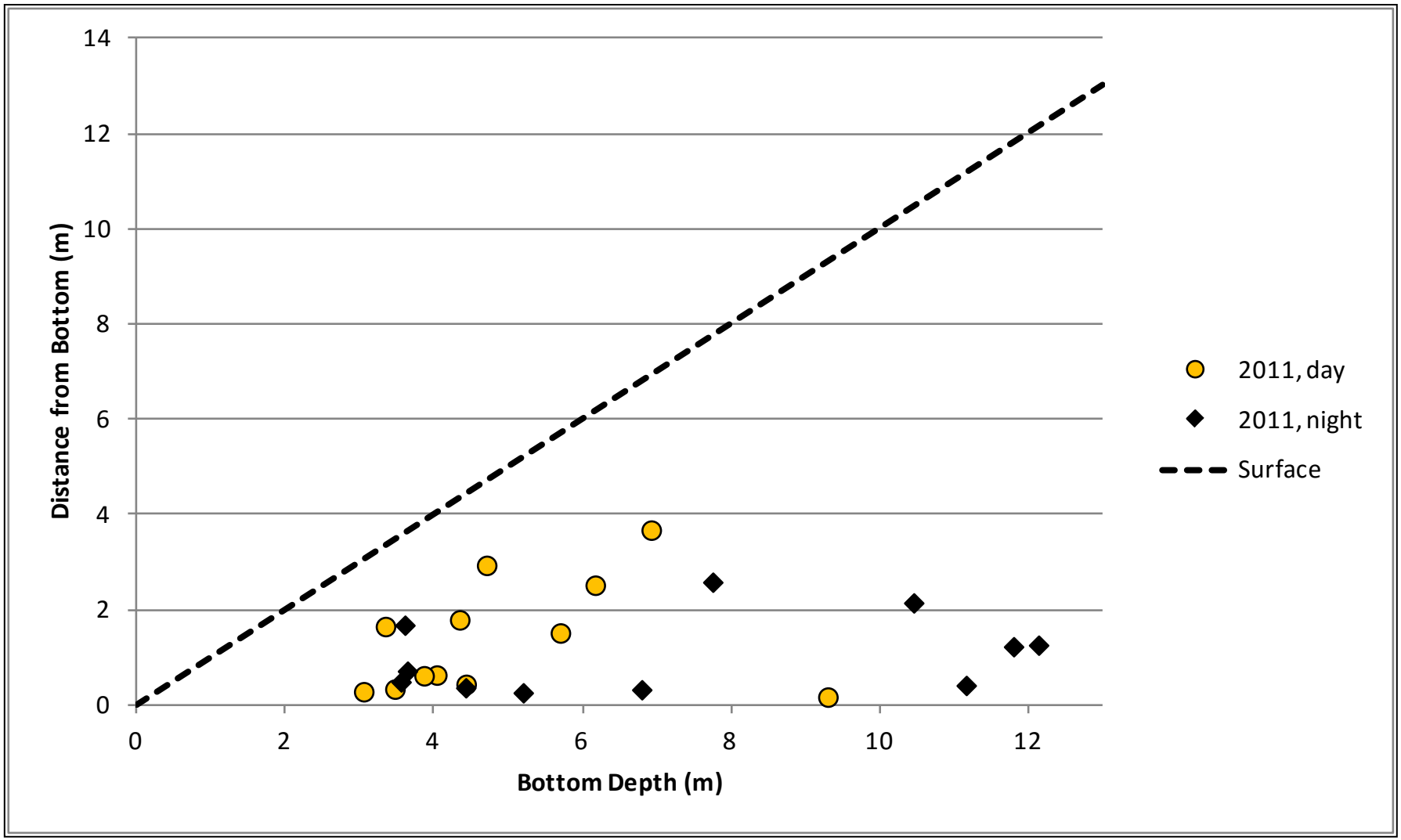
Notes: Dnstr. = downstream; HOR = Head of Old River; HORB = Head of Old River Barrier; m = meters; SJR = San Joaquin River; Upstr. = upstream
Source: Present study



Sources: Google Earth Pro 2012; DWR 2012; Present study

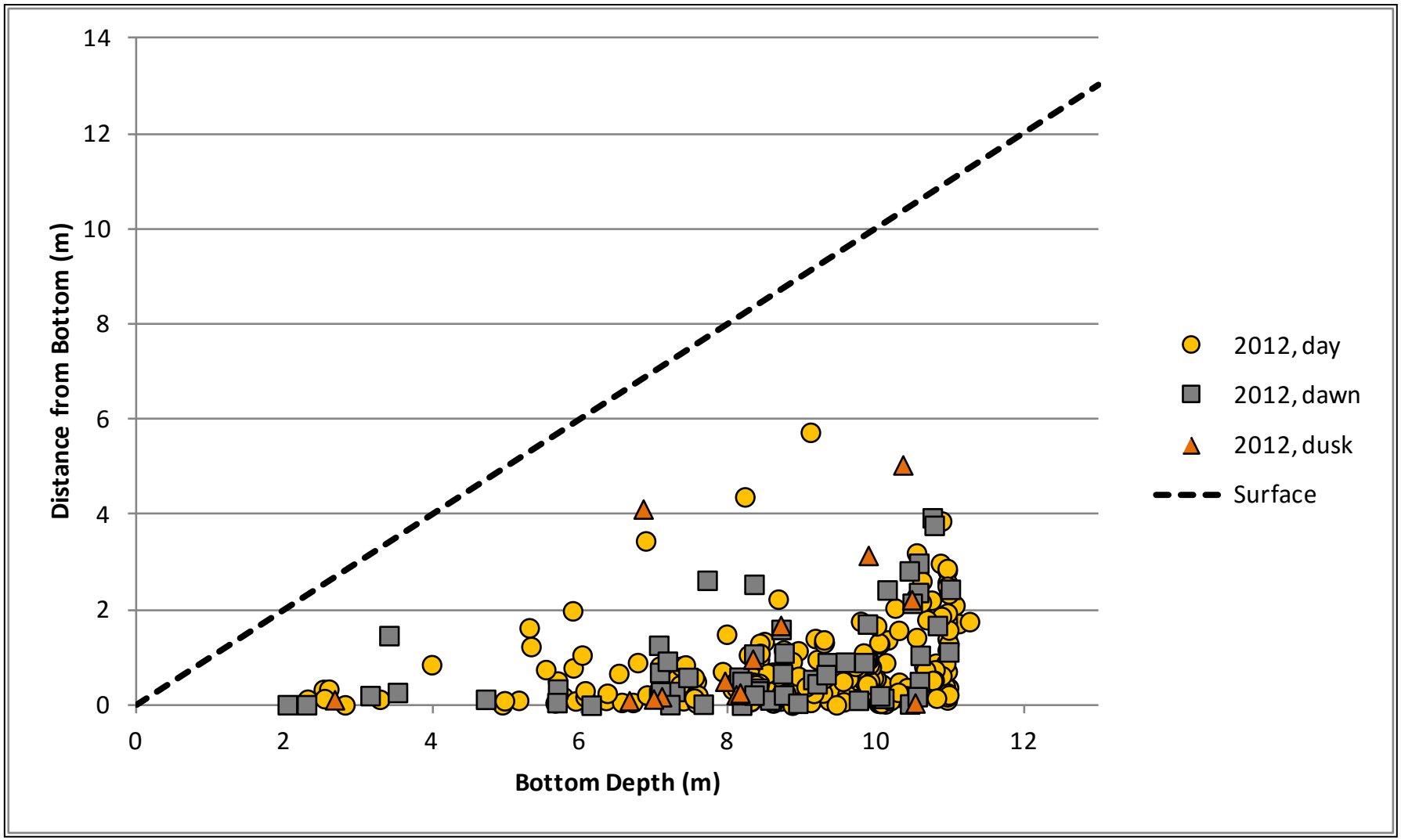
Figure 6-32

Locations of Fish Estimated to be >30 Centimeters Total Length from Side-Looking Mobile Hydroacoustic Surveys, 2011 and 2012



Source: Present study

Figure 6-33 **Distance from River Bottom of Individual Fish Echoes Estimated to be >30 Centimeters Total Length as a Function of Bottom Depth, as Detected during the Day and Night in Down-Looking Mobile Hydroacoustic Surveys in 2011**



Source: Present study

Figure 6-34 **Distance from River Bottom of Individual Fish Echoes Estimated to be >30 Centimeters Total Length as a Function of Bottom Depth, as Detected during the Day, Dawn, and Dusk in Down-Looking Mobile Hydroacoustic Surveys in 2012**

DENSITY CHANGES AND COMPARISONS TO REFERENCE SITES

Density Changes

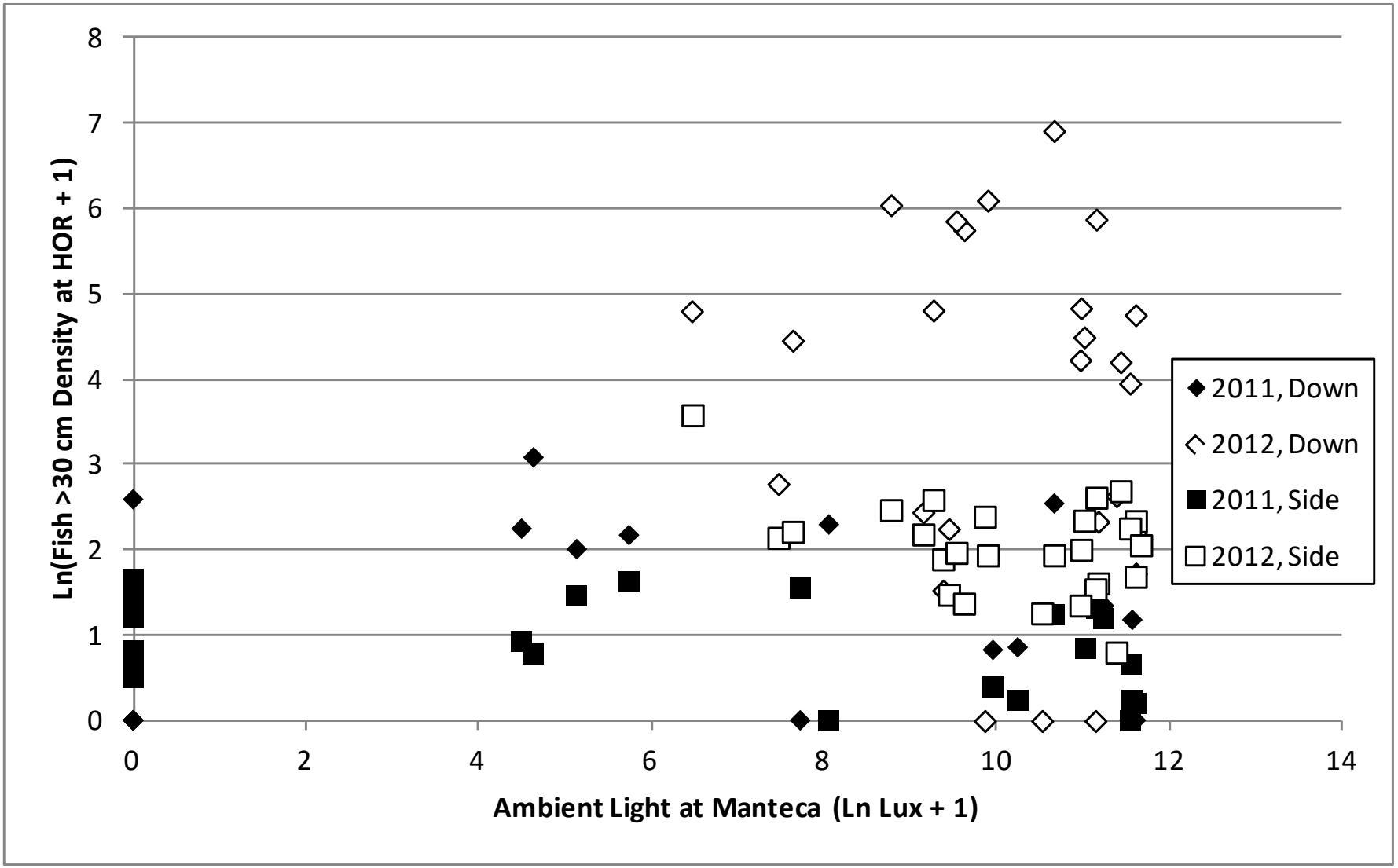
The density of large fish (greater than 30 cm TL) estimated from down-looking mobile hydroacoustic surveys generally was considerably greater in 2012 (mean = 146 fish per 10,000 m^3, median = 66.6 fish per 10,000 m^3) than 2011 (mean = 3.9 fish per 10,000 m^3, median = 1.4 fish per 10,000 m^3). Figures of down-looking density from each survey are presented in relation to environmental variables (discharge, water temperature, turbidity, and small-fish density) for 2011 (Figures G-1, G-2, G-3, and G-4 in Appendix G, "Plots of Environmental Variables and Large-Fish Density from Mobile Hydroacoustic Surveys") and 2012 (Figures G-5, G-6, G-7, and G-8 in Appendix G). The 2011 surveys occurred between May 16 and June 8, and density ranged from zero (10 of 23 surveys) to more than 20 fish per 10,000 m^3 on May 23 (night). In 2012, surveys occurred between March 8 and May 31 (no surveys occurred in April during rock barrier construction), with density ranging from zero (3 of 26 surveys) to more than 1,000 fish per 10,000 m^3 at dusk on May 23. Density in 2012 generally was greater after the physical rock barrier was installed, during higher water temperatures (Figure G-6 in Appendix G).

The density of large fish (greater than 30 cm TL) estimated from side-looking mobile hydroacoustic surveys generally was considerably greater in 2012 (mean = 8.0 fish per 10,000 m^3, median = 6.6 fish per 10,000 m^3) than in 2011 (mean = 1.7 fish per 10,000 m^3, median = 1.4 fish per 10,000 m^3). Figures of side-looking density from each survey are presented in relation to environmental variables in 2011 (Figures G-9, G-10, G-11, and G-12 in Appendix G) and 2012 (Figures G-13, G-14, G-15, and G-16 in Appendix G). Density in 2011 surveys ranged from zero (2 of 23 surveys) to more than 4.2 fish per 10,000 m^3 on May 25 (night). Density in 2012 surveys ranged from just more than 1.2 fish per 10,000 m^3 on March 8 (day) to nearly 35 fish per 10,000 m^3 at dawn on May 23. As with the down-looking data, density in 2012 generally was greater after the physical rock barrier was installed, during higher water temperatures (Figure G-14 in Appendix G).

Plots of the hydroacoustic data included in the GLM analyses (Figures 6-35, 6-36, 6-37, 6-38, and 6-39) showed evidence for greater density of large fish with higher water temperature and lower discharge.

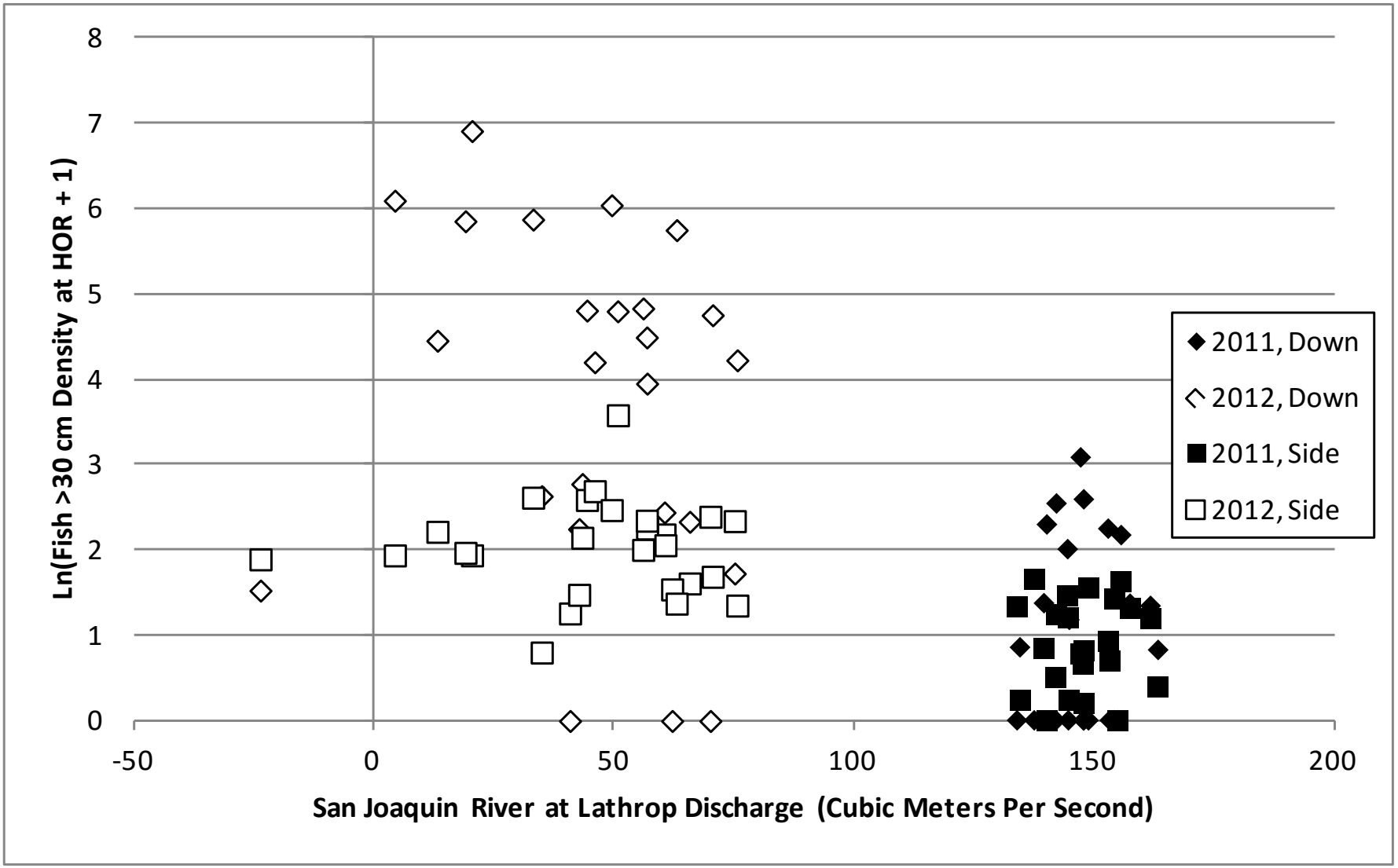
GLM and model-averaging suggested support for same-day discharge and water temperature as predictors of large-fish density from down-looking surveys at the HOR study area, as indicated by predictor coefficients with 95% confidence intervals excluding zero and importance greater than 0.8 (Tables 6-68 and 6-69). Therefore, the null hypothesis $H14_0$ was rejected for these predictors (see "Objectives and Hypotheses Related to Changes in Density of Predatory Fishes" in Section 1.2.4, "Behavior and Density Changes in Predatory Fishes").

Consistent with the observations from the original data described previously, density was negatively related to discharge and positively related to water temperature. There was little support for any other predictors, so null hypothesis $H14_0$ was accepted for these predictors. The GLMs with predictors included provided a better fit to the data than the intercept-only model: the full model with all predictors was ranked eighth out of 32 total models and had the quasi-likelihood equivalent of AIC corrected for small sample sizes ($QAIC_c$) of 255.8, in comparison to $QAIC_c$ of 282.1 for the intercept-only model (ranked last of all models) (Table 6-70). The GLMs using 7-day-mean predictors also suggested support for water temperature as a predictor of large-fish density (Table 6-68). However, the full model had a higher $QAIC_c$ (266.1; 26th-ranked model) (Table 6-71) than the full model for same-day predictors (255.8), suggesting that the model-averaged coefficients based on same-day predictors provided a better fit to the data.



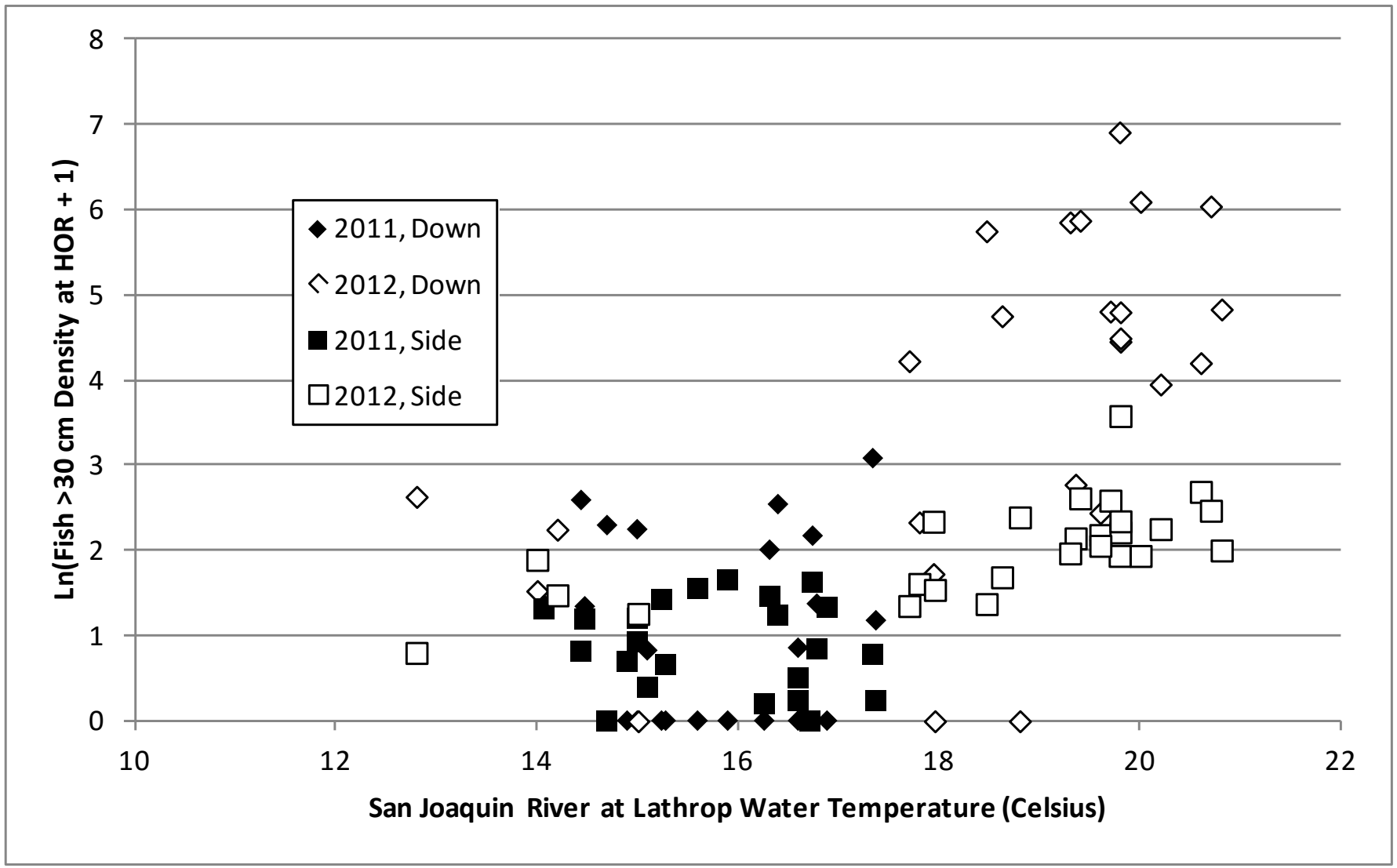
Source: Present study

Figure 6-35 **Estimated Density of Fish >30 Centimeters Total Length in Relation to Ambient Light for 2011 and 2012 Down- and Side-Looking Mobile Hydroacoustic Surveys**



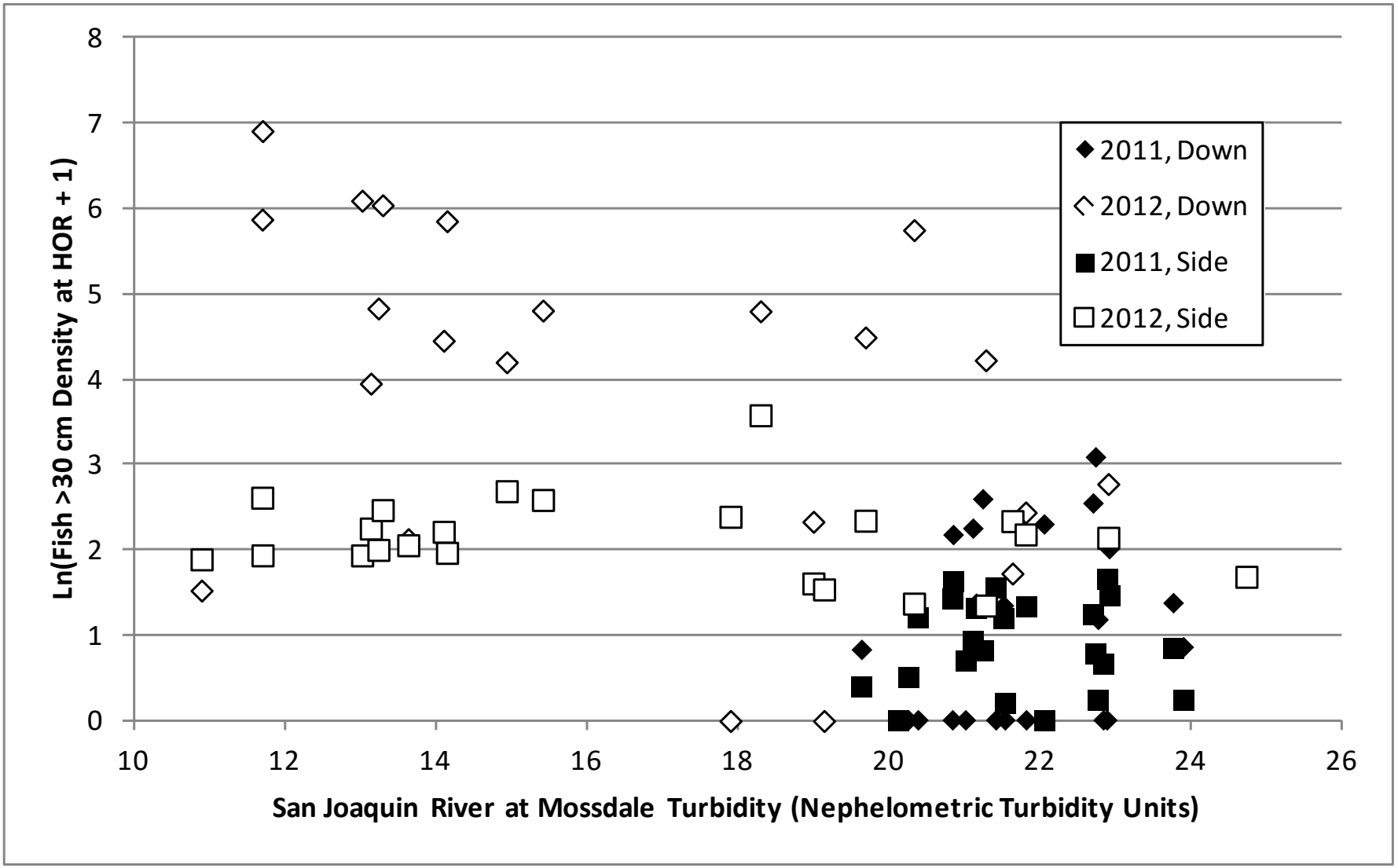
Source: Present study

Figure 6-36 **Estimated Density of Fish >30 Centimeters Total Length in Relation to River Discharge for 2011 and 2012 Down- and Side-Looking Mobile Hydroacoustic Surveys**



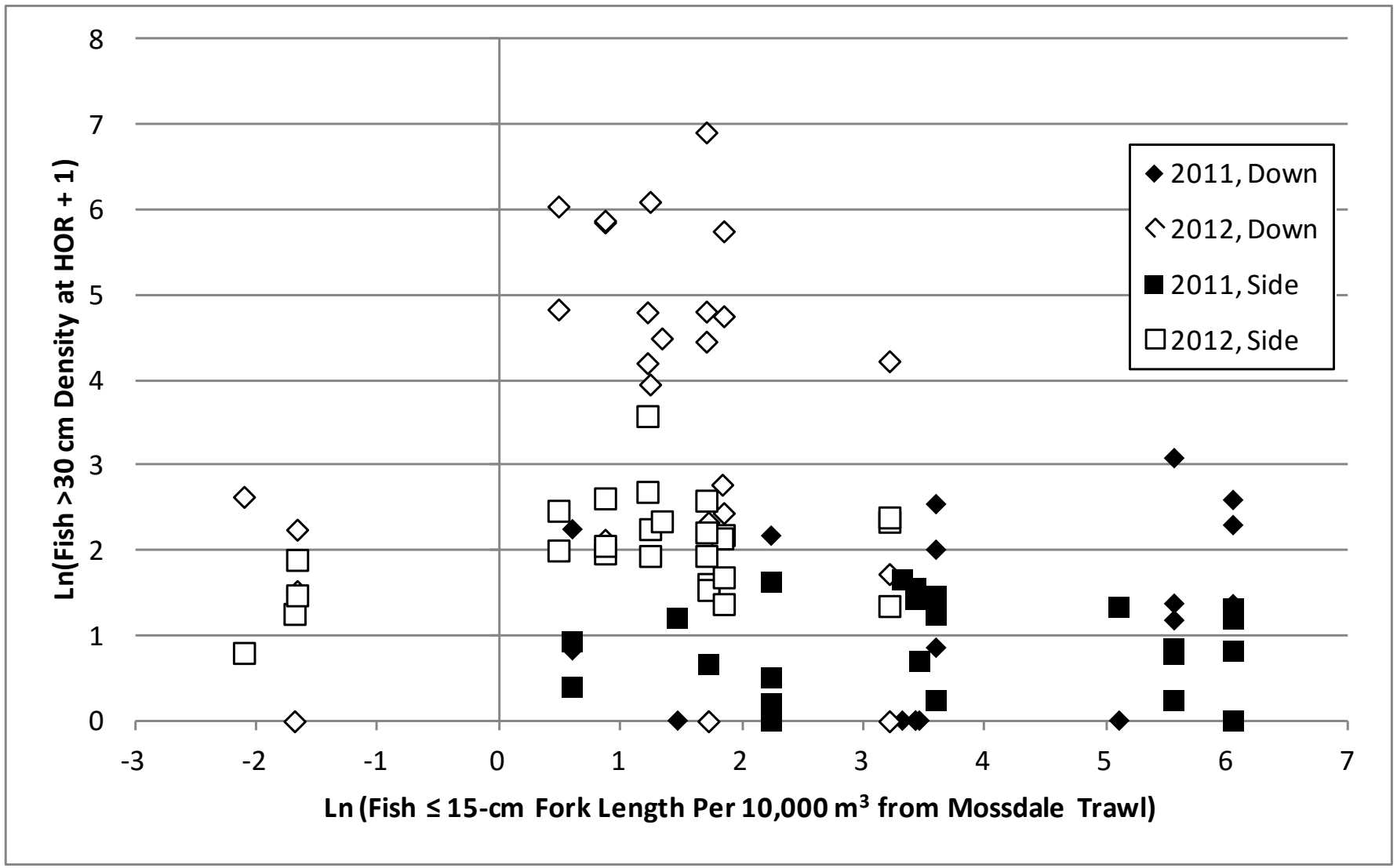
Source: Present study

Figure 6-37 **Estimated Density of Fish >30 Centimeters Total Length in Relation to Water Temperature for 2011 and 2012 Down- and Side-Looking Mobile Hydroacoustic Surveys**



Source: Present study

Figure 6-38 **Estimated Density of Fish >30 Centimeters Total Length in Relation to Turbidity for 2011 and 2012 Down- and Side-Looking Mobile Hydroacoustic Surveys**



Source: Present study

Figure 6-39 **Estimated Density of Fish >30 Centimeters Total Length in Relation to Density of Fish ≤ 15 Centimeters Fork Length from Mossdale Trawling for 2011 and 2012 Down- and Side-Looking Mobile Hydroacoustic Surveys**

Table 6-68
Model-Averaged Coefficients, 95% Confidence Limits, and Variable Importance for the Generalized Linear Modeling of Changes in Density of Large Fish (>30 Centimeters Total Length) from Down-Looking Mobile Hydroacoustic Surveys as a Function of 7-Day Environmental Variables

Variable	Estimate	95% Confidence Limits		Importance
		Lower	Upper	
Water Temperature	0.693	0.354	1.032	0.97
Discharge	-0.013	-0.035	0.009	0.69
Small-Fish Density	0.064	-0.220	0.349	0.35
Turbidity	-0.031	-0.169	0.107	0.32
Ambient Light Level	-0.005	-0.042	0.032	0.22

Source: Present study

Table 6-69
Model-Averaged Coefficients, 95% Confidence Limits, and Variable Importance for the Generalized Linear Modeling of Changes in Density of Large Fish (>30 Centimeters Total Length) from Down-Looking Mobile Hydroacoustic Surveys as a Function of Same-Day Environmental Variables

Variable	Estimate	95% Confidence Limits		Importance
		Lower	Upper	
Discharge	-0.024	-0.040	-0.007	0.95
Water Temperature	0.357	0.022	0.692	0.86
Small-Fish Density	0.101	-0.179	0.381	0.51
Ambient Light Level	-0.004	-0.038	0.030	0.23
Turbidity	-0.003	-0.035	0.029	0.15

Source: Present study

Table 6-70
Model Fit and Weight for Generalized Linear Modeling of Changes in Density of Large Fish (>30 Centimeters Total Length) from Down-Looking Mobile Hydroacoustic Surveys as a Function of Same-Day Environmental Variables

Model Rank	Variables	$QAIC_c$	w_i
1	Intercept + Discharge + Temperature	252.760	0.218
2	Intercept + Small-Fish Density + Discharge + Temperature	253.237	0.172
3	Intercept + Small-Fish Density + Discharge + Temperature + Turbidity	253.237	0.172
4	Intercept + Ambient Light + Discharge + Temperature	255.138	0.066
5	Intercept + Discharge + Temperature + Turbidity	255.238	0.063
6	Intercept + Discharge	255.728	0.049
7	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature	255.774	0.048
8	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature + Turbidity	255.774	0.048
9	Intercept + Small-Fish Density + Discharge	256.476	0.034
10	Intercept + Temperature + Turbidity	257.222	0.023
11	Intercept + Ambient Light + Discharge + Temperature + Turbidity	257.724	0.018
12	Intercept + Discharge + Turbidity	257.932	0.016
13	Intercept + Ambient Light + Discharge	258.080	0.015
14	Intercept + Ambient Light + Small-Fish Density + Discharge	258.947	0.010
15	Intercept + Small-Fish Density + Discharge + Turbidity	258.953	0.010
16	Intercept + Small-Fish Density + Temperature + Turbidity	259.484	0.008
17	Intercept + Ambient Light + Temperature + Turbidity	259.500	0.007
18	Intercept + Temperature	260.013	0.006
19	Intercept + Ambient Light + Discharge + Turbidity	260.369	0.005
20	Intercept + Small-Fish Density + Temperature	261.245	0.003
21	Intercept + Ambient Light + Temperature	261.455	0.003
22	Intercept + Ambient Light + Small-Fish Density + Discharge + Turbidity	261.538	0.003
23	Intercept + Ambient Light + Small-Fish Density + Temperature	263.388	0.001
24	Intercept + Ambient Light + Small-Fish Density + Temperature + Turbidity	263.388	0.001
25	Intercept + Ambient Light + Turbidity	272.783	0.000
26	Intercept + Turbidity	274.698	0.000
27	Intercept + Ambient Light + Small-Fish Density + Turbidity	275.166	0.000
28	Intercept + Small-Fish Density + Turbidity	275.333	0.000
29	Intercept + Small-Fish Density	277.677	0.000
30	Intercept + Ambient Light	277.763	0.000
31	Intercept + Ambient Light + Small-Fish Density	278.070	0.000
32	*Intercept Only*	*282.148*	*0.000*

Notes: $QAIC_c$ = Akaike's Information Criterion adjusted for small sample sizes, accounting for overdispersion; w_i = weight
Source: Present study

Table 6-71
Model Fit and Weight for Generalized Linear Modeling of Changes in Density of Large Fish (>30 Centimeters Total Length) from Down-Looking Mobile Hydroacoustic Surveys as a Function of 7-Day Environmental Variables

Model Rank	Variables	$QAIC_c$	w_i
1	Intercept + Discharge + Temperature	255.029	0.219
2	Intercept + Temperature + Turbidity	255.832	0.147
3	Intercept + Small-Fish Density + Discharge + Temperature	256.241	0.120
4	Intercept + Small-Fish Density + Discharge + Temperature + Turbidity	256.241	0.120
5	Intercept + Ambient Light + Discharge + Temperature	257.309	0.070
6	Intercept + Ambient Light + Discharge + Temperature + Turbidity	257.309	0.070
7	Intercept + Discharge + Temperature + Turbidity	257.509	0.063
8	Intercept + Small-Fish Density + Temperature + Turbidity	258.254	0.044
9	Intercept + Ambient Light + Temperature + Turbidity	258.272	0.043
10	Intercept + Small-Fish Density + Temperature	259.008	0.030
11	Intercept + Temperature	259.714	0.021
12	Intercept + Small-Fish Density + Discharge + Turbidity	260.883	0.012
13	Intercept + Ambient Light + Temperature	261.349	0.009
14	Intercept + Ambient Light + Small-Fish Density + Temperature	261.440	0.009
15	Intercept + Ambient Light + Small-Fish Density + Temperature + Turbidity	261.440	0.009
16	Intercept + Discharge + Turbidity	262.761	0.005
17	Intercept + Small-Fish Density + Discharge	263.796	0.003
18	Intercept + Ambient Light + Discharge + Turbidity	265.089	0.001
19	Intercept + Discharge	265.627	0.001
20	Intercept + Ambient Light + Small-Fish Density + Discharge	266.056	0.001
21	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature	266.056	0.001
22	Intercept + Ambient Light + Small-Fish Density + Discharge + Turbidity	266.056	0.001
23	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature + Turbidity	266.056	0.001
24	Intercept + Ambient Light + Discharge	267.995	0.000
25	Intercept + Small-Fish Density	279.895	0.000
26	Intercept + Ambient Light + Small-Fish Density	280.513	0.000
27	Intercept + Ambient Light	281.994	0.000
28	Intercept + Small-Fish Density + Turbidity	282.225	0.000
29	Intercept + Ambient Light + Turbidity	282.508	0.000
30	Intercept + Ambient Light + Small-Fish Density + Turbidity	282.999	0.000
31	Intercept + Turbidity	284.671	0.000
32	*Intercept Only*	*286.484*	*0.000*

Notes: $QAIC_c$ = Akaike's Information Criterion adjusted for small sample sizes, accounting for overdispersion; w_i = weight
Source: Present study

Similar to the down-looking density results, GLM and model-averaging suggested support for same-day discharge (negative relationship) and water temperature (positive relationship) as predictors of the density of large fish from side-looking surveys at the HOR study area (Table 6-72). Null hypothesis $H14_0$ was therefore rejected for these predictors. Note that the upper 95% confidence interval for discharge is 0.000. No other predictors were supported through model-averaging; $H14_0$ was accepted for these predictors. Inclusion of predictors improved the fit of the model to the data (full model $QAIC_c = 300.5$, intercept-only model $QAIC_c = 320.5$) (Table 6-73). Water temperature was also supported as a predictor of side-looking density for 7-day-mean predictor data (Table 6-74), although the full model had a $QAIC_c$ (303.9) (Table 6-75) that was more than three units greater than the $QAIC_c$ for the full model based on same-day predictors (300.5). As with down-looking density data, this suggests that the model-averaged coefficients based on same-day predictors provided a better fit to the data.

Table 6-72
Model-Averaged Coefficients, 95% Confidence Limits, and Variable Importance for Generalized Linear Modeling of Density Changes of Large Fish (>30 Centimeters Total Length) from Side-Looking Mobile Hydroacoustic Surveys as a Function of Same-Day Environmental Variables

Variable	Estimate	95% Confidence Limits		Importance
		Lower	Upper	
Water Temperature	0.205	0.057	0.354	0.93
Discharge	-0.008	-0.016	0.000	0.87
Ambient Light Level	-0.025	-0.090	0.041	0.47
Small-Fish Density	0.009	-0.069	0.087	0.35
Turbidity	-0.001	-0.022	0.020	0.20

Source: Present study

Table 6-73
Model Fit and Weight for Generalized Linear Modeling of Density Changes of Large Fish (>30 Centimeters Total Length) from Side-Looking Mobile Hydroacoustic Surveys as a Function of Same-Day Environmental Variables

Model Rank	Variables	$QAIC_c$	w_i
1	Intercept + Discharge + Temperature	298.333	0.211
2	Intercept + Ambient Light + Discharge + Temperature	298.432	0.201
3	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature	300.508	0.071
4	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature + Turbidity	300.508	0.071
5	Intercept + Small-Fish Density + Discharge + Temperature	300.681	0.065
6	Intercept + Small-Fish Density + Discharge + Temperature + Turbidity	300.681	0.065
7	Intercept + Discharge + Temperature + Turbidity	300.730	0.064
8	Intercept + Ambient Light + Discharge + Temperature + Turbidity	300.966	0.057
9	Intercept + Temperature + Turbidity	301.971	0.034
10	Intercept + Small-Fish Density + Temperature	302.442	0.027
11	Intercept + Temperature	303.361	0.017
12	Intercept + Discharge	303.392	0.017
13	Intercept + Ambient Light + Temperature + Turbidity	303.445	0.016
14	Intercept + Ambient Light + Discharge	303.998	0.012
15	Intercept + Small-Fish Density + Temperature + Turbidity	304.167	0.011
16	Intercept + Ambient Light + Small-Fish Density + Temperature	304.480	0.010
17	Intercept + Ambient Light + Small-Fish Density + Temperature + Turbidity	304.480	0.010
18	Intercept + Discharge + Turbidity	304.543	0.009
19	Intercept + Small-Fish Density + Discharge	305.016	0.007
20	Intercept + Ambient Light + Small-Fish Density + Discharge	305.105	0.007
21	Intercept + Ambient Light + Discharge + Turbidity	305.304	0.006
22	Intercept + Ambient Light + Temperature	305.658	0.005
23	Intercept + Small-Fish Density + Discharge + Turbidity	306.807	0.003
24	Intercept + Ambient Light + Small-Fish Density + Discharge + Turbidity	307.255	0.002
25	Intercept + Small-Fish Density	317.184	0.000
26	Intercept + Turbidity	318.391	0.000
27	Intercept + Small-Fish Density + Turbidity	318.972	0.000
28	Intercept + Ambient Light + Small-Fish Density	319.461	0.000
29	*Intercept Only*	*320.544*	*0.000*
30	Intercept + Ambient Light + Turbidity	320.728	0.000
31	Intercept + Ambient Light + Small-Fish Density + Turbidity	321.437	0.000
32	Intercept + Ambient Light	322.063	0.000

Notes: $QAIC_c$ = Akaike's Information Criterion adjusted for small sample sizes, accounting for overdispersion; w_i = weight
Source: Present study

Table 6-74
Model-averaged Coefficients, 95% Confidence Limits, and Variable Importance for Generalized Linear Modeling of Density Changes for Large Fish (>30 Centimeters Total Length) from Side-Looking Mobile Hydroacoustic Surveys as a Function of 7-Day Environmental Variables

Variable	Estimate	95% Confidence Limits		Importance
		Lower	Upper	
Water Temperature	0.362	0.204	0.521	1.00
Ambient Light Level	-0.059	-0.136	0.019	0.77
Turbidity	-0.076	-0.196	0.044	0.65
Discharge	-0.003	-0.012	0.006	0.35
Small-Fish Density	-0.007	-0.044	0.030	0.09

Source: Present study

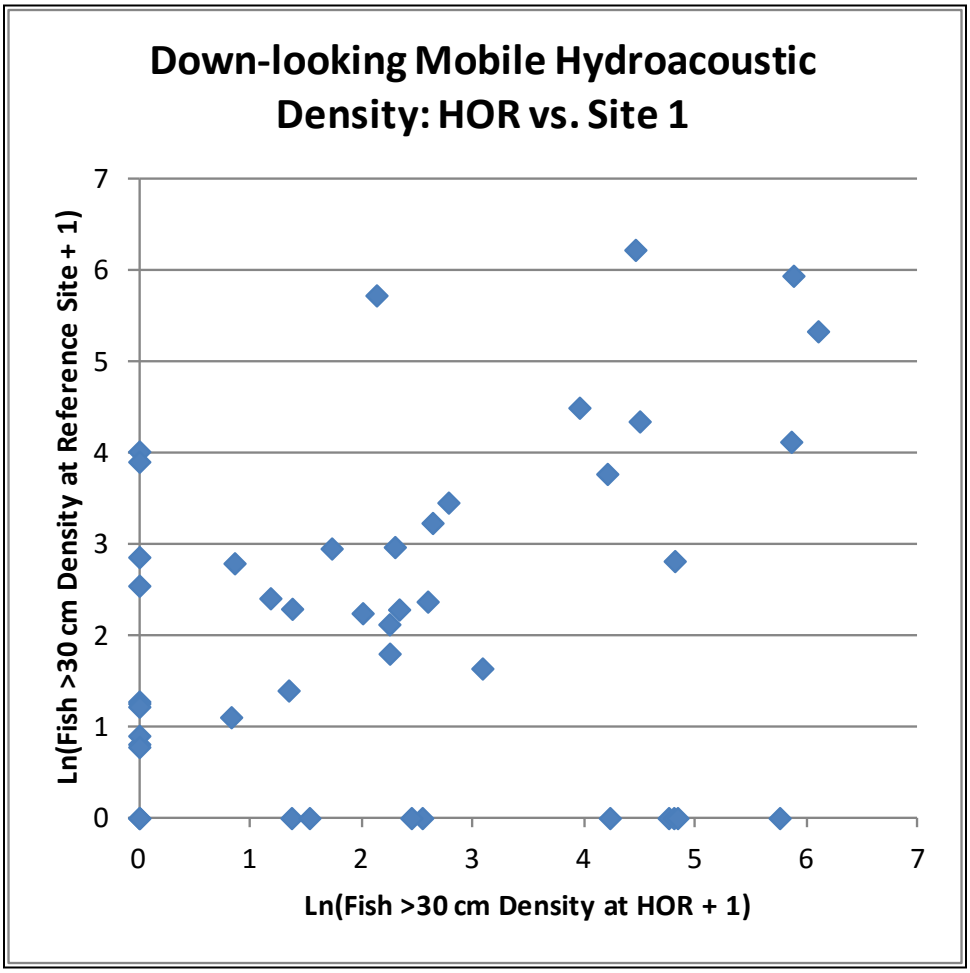
Table 6-75
Model Fit and Weight for Generalized Linear Modeling of Density Changes for Large Fish (>30 Centimeters Total Length) from Side-Looking Mobile Hydroacoustic Surveys as a Function of 7-Day Environmental Variables

Model Rank	Variables	$QAIC_c$	w_i
1	Intercept + Ambient Light + Temperature + Turbidity	289.010	0.485
2	Intercept + Ambient Light + Discharge + Temperature	291.663	0.129
3	Intercept + Ambient Light + Discharge + Temperature + Turbidity	291.663	0.129
4	Intercept + Temperature + Turbidity	292.120	0.102
5	Intercept + Discharge + Temperature	294.228	0.036
6	Intercept + Small-Fish Density + Temperature + Turbidity	294.589	0.030
7	Intercept + Discharge + Temperature + Turbidity	294.605	0.030
8	Intercept + Ambient Light + Small-Fish Density + Temperature	296.426	0.012
9	Intercept + Ambient Light + Small-Fish Density + Temperature + Turbidity	296.426	0.012
10	Intercept + Small-Fish Density + Temperature	296.487	0.012
11	Intercept + Small-Fish Density + Discharge + Temperature	296.707	0.010
12	Intercept + Small-Fish Density + Discharge + Temperature + Turbidity	296.707	0.010
13	Intercept + Temperature	301.578	0.001
14	Intercept + Ambient Light + Discharge	302.974	0.000
15	Intercept + Discharge	303.067	0.000
16	Intercept + Ambient Light + Discharge + Turbidity	303.818	0.000
17	Intercept + Ambient Light + Temperature	303.829	0.000
18	Intercept + Ambient Light + Small-Fish Density + Discharge	303.860	0.000
19	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature	303.860	0.000
20	Intercept + Ambient Light + Small-Fish Density + Discharge + Turbidity	303.860	0.000
21	Intercept + Ambient Light + Small-Fish Density + Discharge + Temperature + Turbidity	303.860	0.000
22	Intercept + Discharge + Turbidity	304.119	0.000
23	Intercept + Small-Fish Density + Discharge	304.531	0.000
24	Intercept + Small-Fish Density + Discharge + Turbidity	306.075	0.000
25	Intercept + Small-Fish Density	312.476	0.000
26	Intercept + Ambient Light + Small-Fish Density	314.740	0.000
27	Intercept + Small-Fish Density + Turbidity	314.755	0.000
28	Intercept + Turbidity	315.641	0.000
29	Intercept + Ambient Light + Small-Fish Density + Turbidity	317.117	0.000
30	Intercept + Ambient Light + Turbidity	318.010	0.000
31	*Intercept only*	*318.914*	*0.000*
32	Intercept + Ambient Light	320.436	0.000

Notes: $QAIC_c$ = Akaike's Information Criterion adjusted for small sample sizes, accounting for overdispersion; w_i = weight
Source: Present study

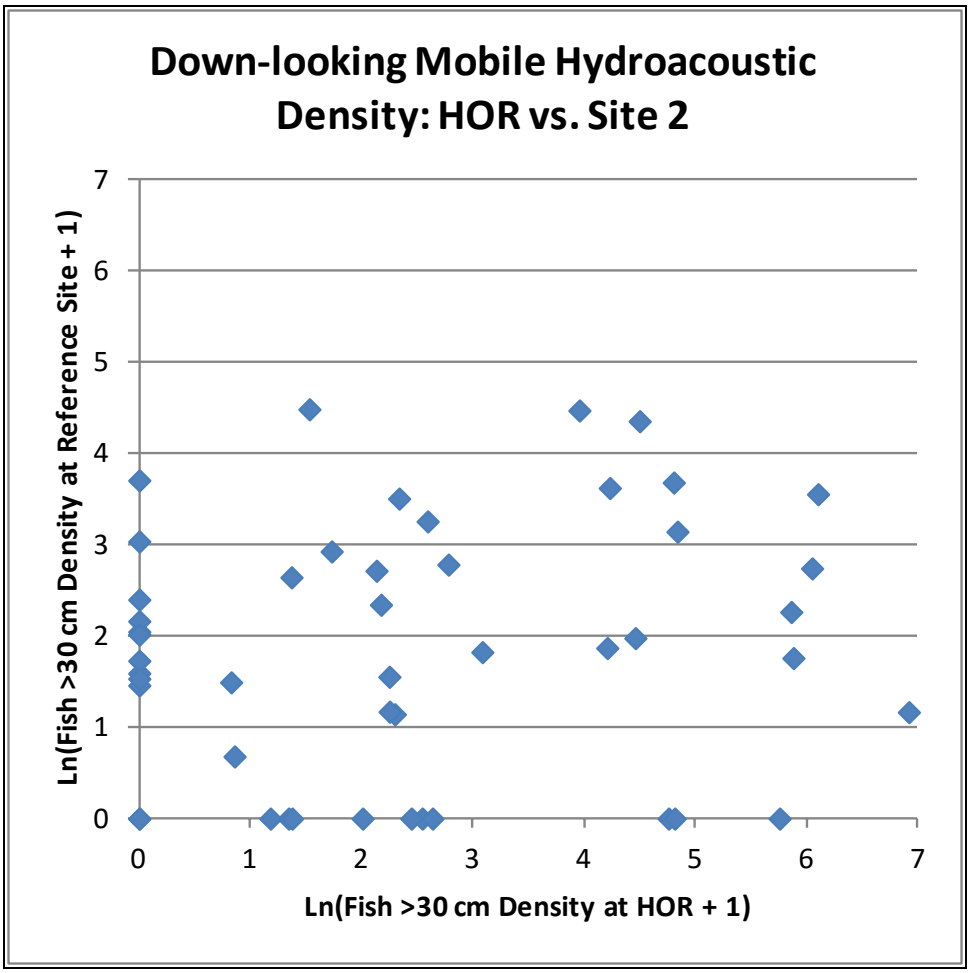
Comparisons to Reference Sites

There was considerable variability in the density of large fish (>30 cm TL) as estimated from down-looking mobile hydroacoustic surveys at the HOR study area and at the reference sites (Figures 6-40, 6-41, and 6-42). There was a statistically significant (P = 0.01) positive correlation between density at the HOR study area and density at Site 4 (San Joaquin River downstream of the HOR study area) (Figure 6-42), which led to rejection of null hypothesis $H15_0$ (See "Objectives and Hypotheses Related to Changes in Density of Predatory Fishes" in Section 1.2.4, "Behavior and Density Changes in Predatory Fishes,"). However, there was no significant correlation between density at the HOR study area and density at the other two sites (allowing acceptance of $H15_0$) (Table 6-76). The density of large fish from down-looking surveys at the HOR site was significantly greater than at Site 4 (P <0.0001), leading to rejection of hypothesis $H16_0$, and not significantly different from density at Sites 1 and 2 (hypothesis $H16_0$ was accepted for these comparisons).



Source: Present study

Figure 6-40 **Estimated Density of Fish >30 Centimeters Total Length at the HOR Study Area in Relation to Density of Fish at Reference Site 1, 2011 and 2012 Down-Looking Mobile Hydroacoustic Surveys**



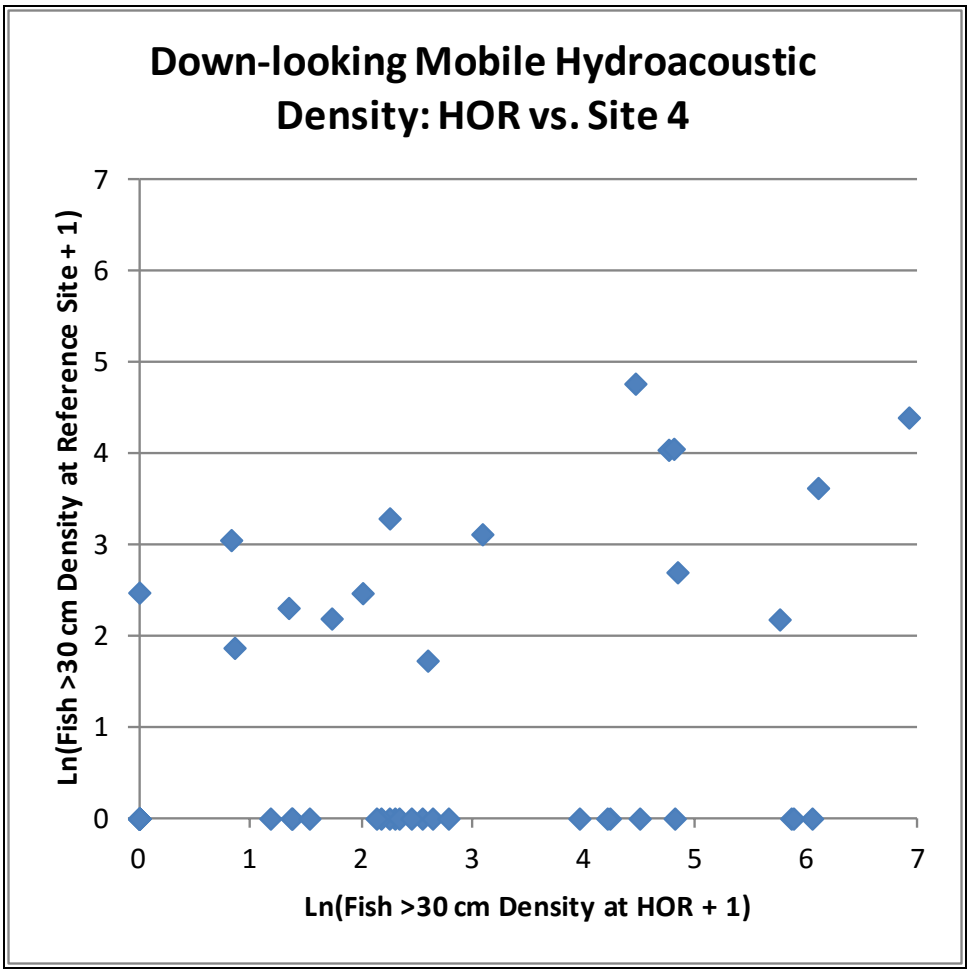
Source: Present study

Figure 6-41 **Estimated Density of Fish >30 Centimeters Total Length at the HOR Study Area in Relation to Density of Fish at Reference Site 2, 2011 and 2012 Down-Looking Mobile Hydroacoustic Surveys**

Table 6-76
Summary of Statistical Tests Comparing Density of Large Fish (>30 Centimeters Total Length) at the Head of Old River Study Area to Reference Sites in the San Joaquin River from Down-Looking Mobile Hydroacoustic Surveys in 2011 and 2012

Comparisons	Correlations		Paired Differences		
	Pearson R	*P* (no. of observations)	Mean Difference (HOR—Reference Site)	Paired T-test t (degrees of freedom)	*P*
HOR vs. Site 1	0.29	0.06 (n = 45)	0.14	0.41 (44 d.f.)	0.68
HOR vs. Site 2	0.14	0.34 (n = 48)	0.62	1.85 (47 d.f.)	0.07
HOR vs. Site 4	**0.37**	**0.01 (n = 48)**	**1.47**	**4.91 (47 d.f.)**	**<0.0001**

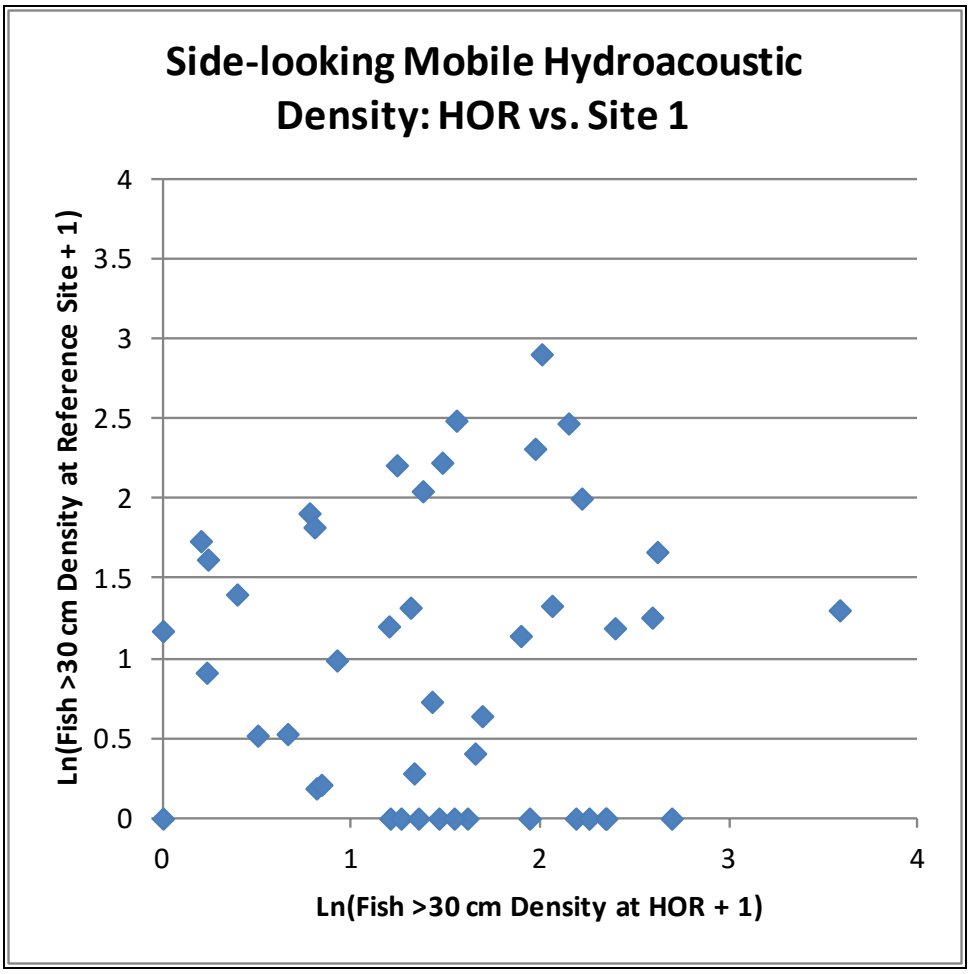
Notes: HOR = Head of Old River study area; n = number of observations; n = number; d.f. = degrees of freedom
Comparisons were based on natural-logarithm-transformed data.
Bold Indicates statistical significance at Bonferroni-adjusted $P < 0.017$.
Source: Present study



Source: Present study

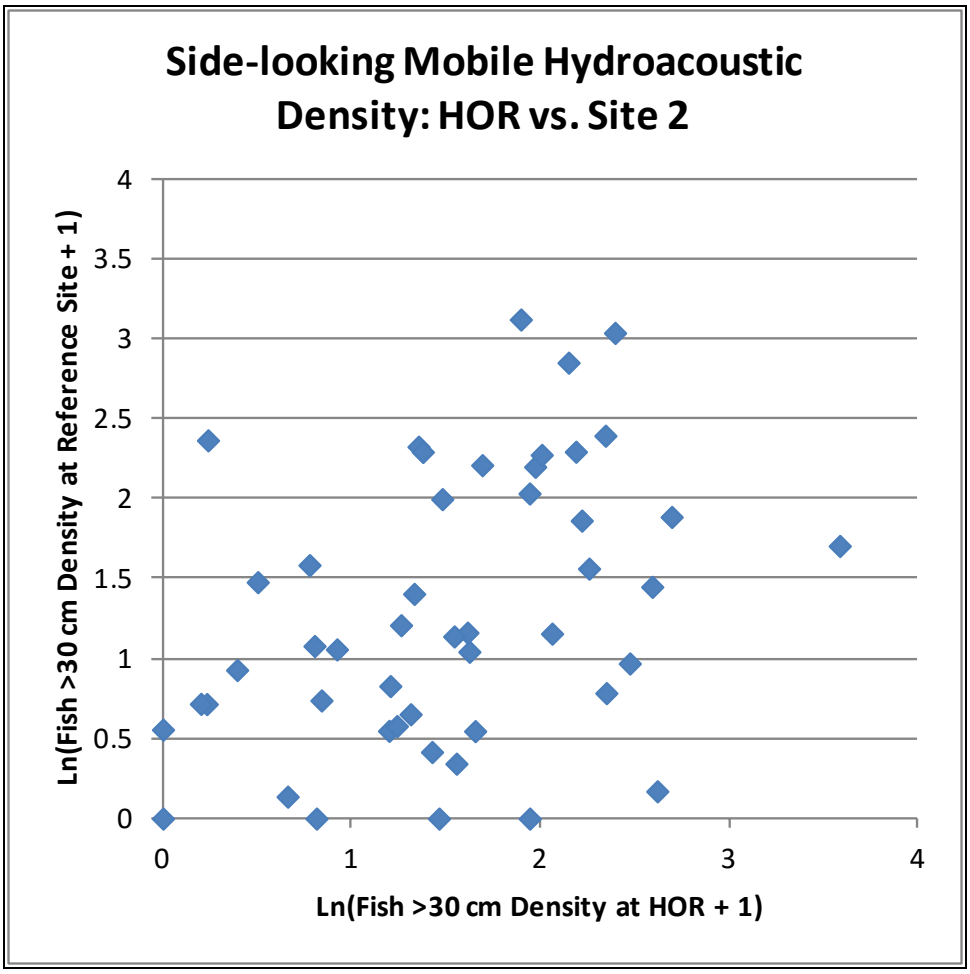
Figure 6-42 **Estimated Density of Fish >30 Centimeters Total Length at the HOR Study Area in Relation to Density of Fish at Reference Site 4, 2011 and 2012 Down-Looking Mobile Hydroacoustic Surveys**

As noted for down-looking density data, appreciable variability in large-fish density was estimated from side-looking mobile hydroacoustic surveys at the HOR study area and at the reference sites (Figures 6-43, 6-44, and 6-45). Statistically significant positive correlations existed between density at the HOR study area and density at Sites 2 and 4 ($P \leq 0.01$) (Table 6-77), so that $H15_0$ was rejected for these comparisons. There was no correlation between density at the HOR study area and density at Site 1 ($H15_0$ was accepted). Density of large fish from side-looking surveys at the HOR study area was significantly greater than at Sites 1 ($P = 0.01$) and 4 ($P < 0.001$), leading to rejection of hypothesis $H16_0$, and not significantly different from density at Site 2 (hypothesis $H16_0$ was accepted) (Table 6-77).



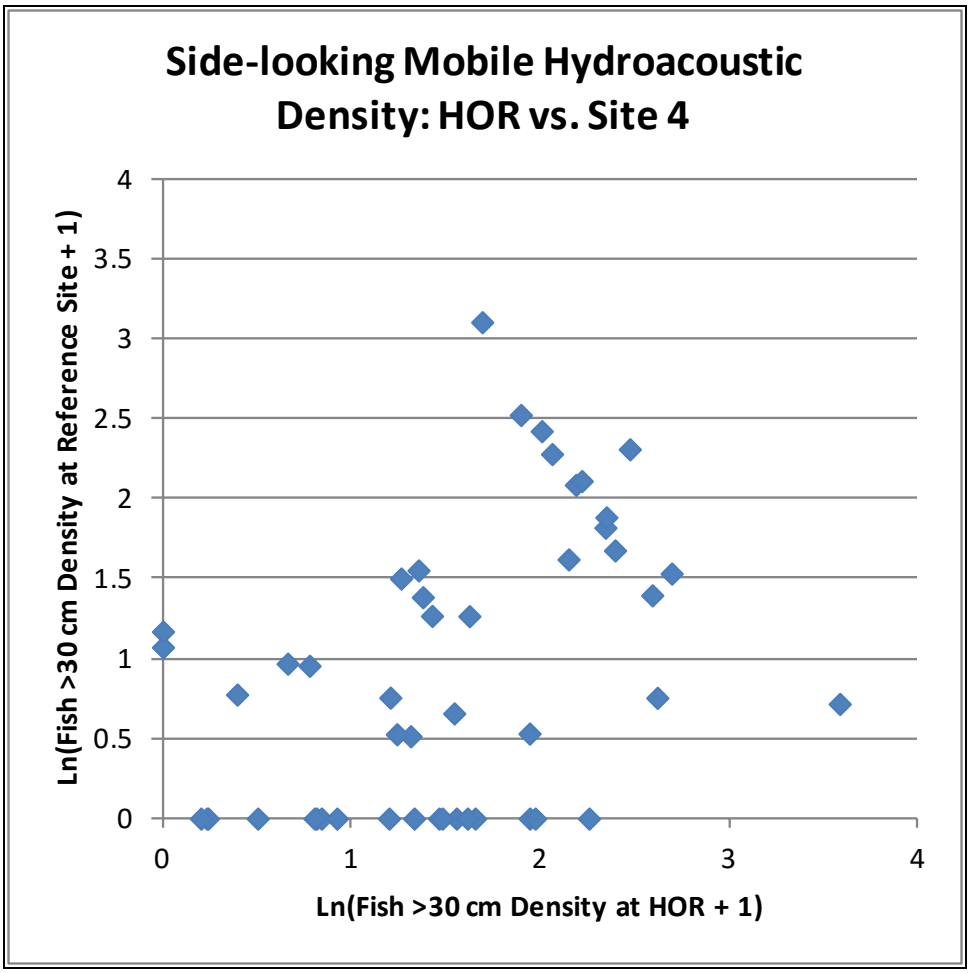
Source: Present study

Figure 6-43 **Estimated Density of Fish >30 Centimeters Total Length at the HOR Study Area in Relation to Density of Fish at Reference Site 1, 2011 and 2012 Side-Looking Mobile Hydroacoustic Surveys**



Source: Present study

Figure 6-44 **Estimated Density of Fish >30 Centimeters Total Length at the HOR Study Area in Relation to Density of Fish at Reference Site 2, 2011 and 2012 Side-Looking Mobile Hydroacoustic Surveys**



Source: Present study

Figure 6-45 **Estimated Density of Fish >30 Centimeters Total Length at the HOR Study Area in Relation to Density of Fish at Reference Site 4, 2011 and 2012 Side-Looking Mobile Hydroacoustic Surveys**

Table 6-77
Summary of Statistical Tests Comparing Density of Large Fish (>30 Centimeters Total Length) at the Head of Old River Study Area to Reference Sites in the San Joaquin River from Side-Looking Mobile Hydroacoustic Surveys in 2011 and 2012

Comparisons	Correlations		Paired Differences		
	Pearson R	*P* (no. of observations)	Mean difference (HOR—Reference Site)	Paired T-test t (degrees of freedom)	*P*
HOR vs. Site 1	0.01	0.92 (n = 45)	**0.49**	**2.78 (44 d.f.)**	**0.01**
HOR vs. Site 2	**0.37**	**0.01 (n = 48)**	0.22	1.63 (47 d.f.)	0.11
HOR vs. Site 4	**0.41**	**<0.01 (n = 48)**	**0.61**	**4.61 (47 d.f.)**	**<0.0001**

Notes: HOR = Head of Old River study area; No. = number; n = number of observations; d.f. = degrees of freedom
Comparisons were based on natural-logarithm-transformed data.
Bold Indicates statistical significance at Bonferroni-adjusted *P* < 0.017.
Source: Present study

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7 DISCUSSION

7.1 JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

Considerable differences existed between barrier treatments for all dependent variables measured: barrier efficiency, predation rates measured as proportion eaten, and transit speed. In this chapter, the differences between barrier treatments and years are described and compared in tandem, because the associations between barrier treatment and year cannot be separated due to study design. The results of the univariate analyses and proportion eaten are discussed in this chapter because they are closely related. Section 7.2, "Predation on Juvenile Salmonids Including Barrier Effects," focuses on explaining the results from the probability of predation as investigated with generalized linear modeling (GLM). Results related to transit speed are addressed in Appendix D, "Transit Speed Analyses."

7.1.1 2009 BAFF

In 2009, with the BAFF on, overall efficiency ($O_{E)}$ for tagged juvenile Chinook salmon was 20.9% and protection efficiency (P_E) was 33.8% (Tables 6-1 and 6-4). These results were difficult to reconcile with the observed BAFF deterrence efficiency (D_E) of 73.2% (Table 6-7). Two explanations were explored: predation and other factors.

The first explanation for the large gap between O_E and P_E was that a large proportion of the deterred tagged juvenile Chinook salmon subsequently were eaten which decreased O_E. When proportion eaten and the 2D tracks were evaluated for the 2009 data, many tagged juvenile Chinook salmon were determined to have been deterred and then eaten. Therefore, it seems that some of the benefit obtained by the BAFF's deterrence of tagged juvenile Chinook salmon could have been nullified by predation before they successfully migrated past the San Joaquin River finish line.

The difference between D_E and P_E for tagged juvenile Chinook salmon in 2009 was consistent with the striped bass tracking performed in 2011 and 2012. The tracking showed that the scour hole, the San Joaquin River's downstream and upstream offshore areas, and the HOR's upstream offshore areas were the most commonly used places at the HOR study area (Figures 6-19 and 6-21). The data from the mobile hydroacoustic survey also suggested that, in 2011 and 2012, the distribution of the majority of fish greater than 30 cm TL were downstream of the BAFF area (Figures 6-31 and 6-32). Although these data were collected in 2011 and 2012, they support the conclusion that the predator/prey encounter rates may be highest downstream of the 2009 BAFF line. Thus, the 2011 and 2012 data on predators support the conclusion that the difference in D_E and P_E in 2009 may have been caused by predation. Further discussion of areas occupied by predatory fish is provided in Section 7.3.2, "Areas Occupied by Predatory Fishes."

The predation explanation for the 2009 difference between D_E and P_E was consistent with other data collected from 2009 to 2012. Eighty-three percent of stationary/defecated tags were detected in the San Joaquin River downstream of the divergence and of these, 60% were found in the scour hole and 40% were found in the downstream San Joaquin River offshore areas (Figure 6-30). Although the number of stationary tags was small in 2009 and 2010, the pattern was similar through all years studied.

The ability to determine which tags were eaten was imperfect. In 2009, 532 tagged juvenile Chinook salmon released at Durham Ferry passed the San Joaquin River start line (Table 6-57). The total number of tags that passed the finish lines (San Joaquin River and Old River combined) was 410. Therefore, at least 122 perished at the HOR study area. In addition, the proportion of those that were eaten was not definitively determined. It was possible only to estimate the proportion eaten with the data that existed: the 2D tracks. The process by which this was done for tagged juvenile Chinook salmon was expert assessment without validation. No validation was possible because no tagged juvenile Chinook salmon were recaptured to determine the rate of incorrect "eaten" determinations. This error rate for tagged juvenile Chinook salmon therefore, must be estimated. If that error rate is high, many incorrect determinations were made, and the explanation for the discrepancy between 2009 O_E and D_E may not be acceptable. If it is accepted that the error rate is intermediate or small, then it may be concluded that the predation of tagged juvenile Chinook salmon explains some proportion of the difference between O_E and D_E.

The proportion of the difference between O_E and D_E that may be explained by predation was calculated. In 2009, the number of deterred tagged juvenile Chinook salmon was 103 and the number subsequently eaten, after they were deterred, was 36. If those 36 are added in, then the O_E in 2009 under "BAFF On" conditions increases to 36.5%, recall D_E was 73.2%. Thus, predation alone, even if it is accepted that the eaten determination error rate is not high, cannot explain the difference in O_E and D_E.

The second explanation for the large difference between O_E and D_E was the discharge regime in 2009 (Figure 3-2). Many tagged juvenile Chinook salmon were deterred by the BAFF, but may have ultimately exited the HOR study area via Old River because they were transported back on reverse flows. These fish passed between the BAFF and the north shore on reverse flows or passed through the BAFF.

Therefore, predation may account for some of the difference between BAFF deterrence and O_E in 2009. The calculations presented suggest that reverse flows may also have been responsible for some of this difference. Thus, it is concluded that predation on tagged juvenile Chinook salmon that were deterred but exited via Old River, contributed to the difference.

Other researchers working in the south Delta in 2009, including at the HOR study area, found a P_E of 47.4% (SJRGA 2013:155; reproduced in Appendix I, "Route Entrainment Analysis at Head of Old River, 2009 and 2010"). A total of 173 tagged juvenile salmonids passed the San Joaquin River finish line, compared to a total of 365 that passed the Old River or San Joaquin River finish line. This was much higher than the combined (BAFF on and off) P_E of 27.7% reported in this study. At least three reasons explain this difference: (1) the way in which predation was assigned by the two groups; (2) the distance between the San Joaquin River start and finish lines for the two studies; and (3) the fact that in 2009, the San Joaquin River Group Authority (SJRGA) (2013) used one-dimensional detection data (i.e., used one hydrophone's detections at a time), while 2D positions with track visualization were used for this study.

In 2009, the predator classification was based on the acoustic signal pattern through time within the detection of the tag at each individual hydrophone, using the method of Vogel (2010). This method used limited comparison to detections on other Vernalis Adaptive Management Program (VAMP) hydrophones. In this study, predation was assigned using behavior patterns that could be observed with the 2D track visualizations (see Appendix E, "Fish Fate Determination Guidelines"). The method used in the SJRGA (2010) study apparently was less likely to

determine that a tag from a salmonid juvenile had been consumed by a predator compared to the method used in the present study.

The finish line used in this study (Figure 5-13) was approximately 303 m upstream of the finish line used by SJRGA (2010). Within this distance, an unknown amount of predation took place. Those salmonids eaten between the two finish lines would count as protected in this study, and SJRGA (2013) would have determined that those juveniles never arrived at the finish line.

The third difference between these two methodologies was that SJRGA (2013) used one-dimensional detection data. By contrast, in this study, 2D positions with track visualization were used for predation determinations. Which of these techniques is more conservative for predation determinations is unknown. Compared to this study, SJRGA (2013) apparently assigned fewer tags a fate of predation.

The effect of light level was evaluated relative to all three measures of barrier efficiency. The only measure that showed a significant influence from light level was D_E; when compared to the BAFF off, D_E was significantly higher when the BAFF was on (Table 6-9). D_E with the BAFF on during high light conditions was 89.7%. This may reflect a greater ability of tagged juvenile Chinook salmon to orient away from the BAFF's main noxious stimulus (the acoustic deterrent) in high light because of the increased visibility of the BAFF. An analogous situation occurs when fish are able to better avoid water intakes by day than by night in low-turbidity water (Helvey and Dorn 1981). However, a previous BAFF trial in England found greater efficiency by night than by day because the increased daytime visibility possibly allowed Atlantic salmon smolts to pass through gaps in the bubble curtain (Welton et al. 2002). However, in this study, the visual predators at the HOR study area were more likely to prey on juvenile Chinook salmon under daylight conditions. Thus, this exceptionally high deterrence delivered with the BAFF only provided a P_E of 48.4%. The benefit gained by BAFF deterrence appears reduced by predation.

No high-velocity samples were acquired in 2009 because of the low magnitude and negative discharges in the San Joaquin River (Figure 3-2). Thus, evaluating the effect of velocity on BAFF efficiency was not possible.

7.1.2 2010 BAFF

In 2010, "BAFF on" O_E was 35.5% (i.e., including tags preyed on at the HOR study area). When the tags that were determined to have been eaten were removed, the P_E improved substantially by operation of the BAFF (44.1%) (Table 6-15). The combined (BAFF on and BAFF off) P_E for 2010 was 36.1%. In 2010, SJRGA (2011) found that the P_E for "tags-in-juveniles" was 47.0%. As with 2009, the value reported in this study was lower than that of SJRGA (2013).

In Section 7.1.1 three reasons were given to explain this difference: (1) the way in which predation was assigned; (2) the distance between the San Joaquin River start and finish lines for the two studies; and (3) the fact that SJRGA (2011) used one-dimensional detection data, while 2D positions with track visualization were used in this study. The one major difference in methodology between 2009 and 2010 was that SJRGA (2011) used a different method for determining predation. In 2010, predation was assigned by SJRGA (2013:Table 5-8) to tag detections using residence time, migration rate, number of return visits to a hydrophone, discharge, and water velocity. In addition, some special conditions were applied to tag detection patterns regarding tide and pumping by the CVP or SWP. Also, the spatial/temporal pattern of detections throughout the VAMP hydrophone array was considered

as a whole to determine predation, rather than limiting analysis to a single spatial area. Still, the result was the same: SJRGA (2011, 2013) was less likely to assign a fate of predation in 2010 than this study. These factors probably played a role in the difference between the estimate reported in this study and the SJRGA estimate; the relative importance of each factor is unknown.

The difference in D_E with the BAFF on compared to the BAFF off was 13.8%. This was very similar in magnitude to the difference between P_E with the BAFF on and off (15.5%). These results suggest that the BAFF operation was deterring about 14% of the tagged juvenile Chinook salmon that approached the BAFF, and that translated to a similar improvement in P_E. In addition, in 2010, a very low percentage of tagged juvenile Chinook salmon exhibited deterrence with the BAFF off (1.2%).

No difference existed in sample proportion eaten between the BAFF on and off, suggesting that, in 2010, BAFF operation did not increase predation rate over the BAFF infrastructure's effect (Table 6-50). This was in contrast to 2009, when the BAFF on proportion eaten was significantly higher than the BAFF off proportion eaten (Table 6-49).

In 2010, light level was not shown to have a substantial effect on O_E (Table 6-12). As in 2009, it was possible that this lack of significance occurred because of small sample sizes and low statistical power. At high light levels, P_E with the BAFF on was higher than with the BAFF off (P-value = 0.0812; Table 6-17); however, the statistical power of this test was only 0.417. The lack of significance (using a critical α of 0.05) could have been a function of low power; thus, it appeared that at high light levels, there could have been significantly higher P_E with the BAFF on than off. This could have been driven by substantial improvement in D_E at high light levels with the BAFF on relative to off conditions (Table 6-22). These results were similar to those of Bowen et al. (2010), at low turbidities (10 NTU), the highest deterrence was observed at high light levels. These results suggest that for the 2010 juvenile Chinook salmon at the HOR study area, additional visual cues to avoid the BAFF were available to the tagged juvenile Chinook salmon during high light, as noted previously for 2009 data.

Velocity did not affect O_E. However, at low velocity, P_E was 16.9 percentage points higher with the BAFF on than off (Kruskal-Wallis $X^2 = 3.699$; P-value = 0.0544) (Table 6-19). This result may have been a consequence of the tagged juvenile Chinook salmon having had more time to evaluate the BAFF and move away before being swept through. The average channel velocity (ACV) did not affect deterrence; deterrence with the BAFF on was significantly better than BAFF off at both velocity levels evaluated (Table 6-24).

For 2010, D_E was significantly improved with the BAFF on, by about 14 percentage points (Table 6-20). This was reflected in an improvement in P_E with the BAFF on by approximately this same amount. These improvements in D_E and P_E were the largest during high-light conditions. Thus, the BAFF's operation did significantly improve the tagged juvenile Chinook salmon proportion selecting the San Joaquin River route (Table 6-15) (Table I-3 in Appendix I), but BAFF-on conditions also exhibited a population proportion eaten of 31.0% (Table 6-50).

7.1.3 BAFF OPERATIONS: 2009 VS. 2010

No significant difference in O_E occurred with the BAFF on in 2009 versus in 2010; however, the P-value (0.0563) (Table 6-26) and the low statistical power observed for the test, 0.489, suggest that a difference could exist between these years with different BAFF alignments. It was concluded that the low statistical power made it impossible to determine if O_E was higher in 2010 than in 2009.

The difference in O_E and P_E between BAFF on and off status was greater in 2010 than in 2009. At least three phenomena contributed to explaining these differences: (1) the discharge regimes differed; (2) tagged juvenile Chinook salmon differed between the two years; and (3) in 2010, the BAFF alignment was longer and curved more than in 2009 (Figure 4-3).

First, in 2009, BAFF efficiencies (Tables 6-1 and 6-4) and the discharge magnitudes (Figure 3-2; see also Appendix D, "Transit Speed Analyses") were the lowest, and the percentage of flow into the San Joaquin River during the study period was the lowest observed across all years (35%). In 2010, BAFF efficiencies were higher (Tables 6-10 and 6-15), discharge magnitude was intermediate (Figure 3-4), and the percentage of flow into the San Joaquin River was 56% (Table 3-1).

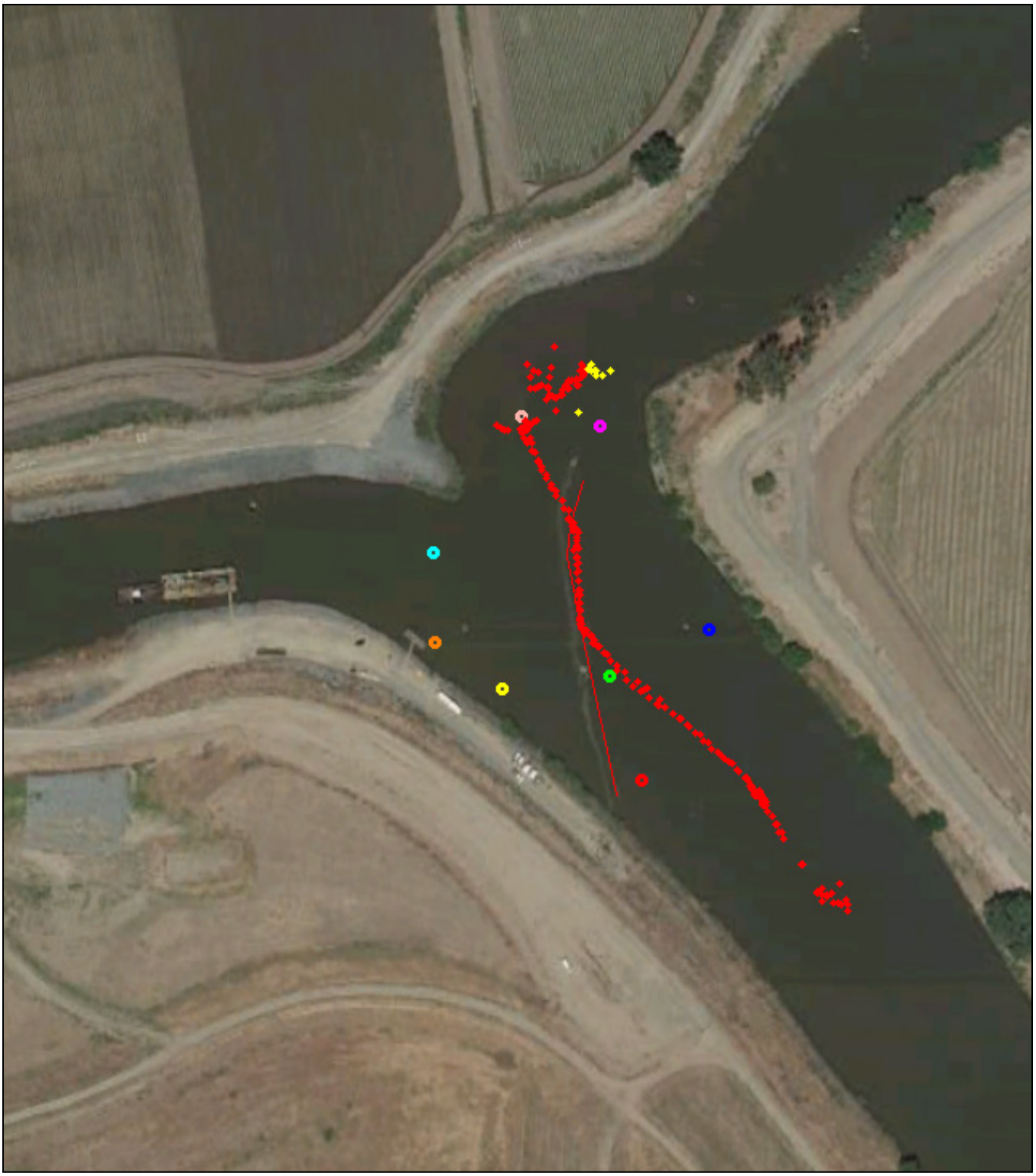
Second, the tagged juvenile Chinook salmon were smaller in 2009, and the tag burden was higher in 2009 than in 2010 (described in Tables 5-1 and 5-3 in Chapter 5, "Methods," and in Section 6.3 in Chapter 6, "Results").

Third, the longer-curved 2010 BAFF alignment could have improved O_E and P_E relative to the 2009 alignment without improving D_E. A number of tagged fish in 2010 were not deterred (by the strict definition of deterrence used in the study), but their route was changed from the Old River to the San Joaquin River (Figure 7-1). This would add to the O_E and P_E values, but not to the D_E value (see discussion by Bowen and Bark [2012]).

Like O_E, P_E was 10.4 percentage points higher in 2010 than 2009, but this difference was not significant. In addition, D_E was significantly higher with the BAFF on than off in both years. This study concluded that a statistically significant but small increase in D_E always occurred during BAFF operation (13.8% to 42.1%), and this deterrence increased P_E in both years. However, the increases in P_E were not significant.

A significantly higher proportion of tagged juvenile Chinook salmon were deterred when the BAFF was off in 2009 than in 2010 (Table 6-30). One possible explanation for this was the difference in discharge patterns between the two years, with negative discharges common in 2009 (Figure 3-2) and no negative discharges during the experimental fish releases occurring in 2010, only positive discharges (see Figure 3-4). A second possible explanation was that higher discharges and concomitant higher stage heights in 2010 meant that the BAFF infrastructure took up a smaller proportion of the water column than in 2009; perhaps a smaller proportion of the fish could sense the turbulence created by the BAFF infrastructure or its visual presence, and they did not move away from it or did not follow the alignment in as great a proportion. Alternatively, the higher deterrence rate with the BAFF off in 2009 compared to 2010 could have been due to the different BAFF alignments in the two years. In 2009, the BAFF alignment was straight, and in 2010 the alignment was curved at the end like a hockey stick (Figure 4-3). Thus, a tagged juvenile Chinook salmon turning once guiding along the BAFF would appear to be deterred in 2009. However, the same path in 2010 might cross the BAFF line, and it would be determined to have been undeterred.

In 2010, no substantial difference occurred between the proportions eaten with the BAFF on and off (Table 6-50). However, in 2009, the proportion eaten was significantly higher with the BAFF on than off (Table 6-49). There were no differences in the proportions eaten between 2009 and 2010 for both the BAFF on and off (Table 6-52), suggesting somewhat similar levels of predation in both years.



Note: This tagged juvenile Chinook salmon was determined to have been "not deterred," was guided along the BAFF, passed into the San Joaquin River where it was determined to have not been eaten, and successfully passed the San Joaquin River finish line.

Source: Data compiled by Hydroacoustic Technology Inc. this study

Figure 7-1 **Tagged Juvenile Chinook Salmon Number 5353.14 2D Track through the Head of Old River Study Area in 2010**

The 2011 and 2012 GLM modeling of changes in predator density from downward- and sideward-looking hydroacoustics suggests another possible mechanism besides tag burden and turbidity. The GLM modeling showed a negative relationship between same-day discharge and the density of large fish greater than 30 cm TL (Section 6.3.2, "Hydroacoustic Data"). The same-day discharges in 2009 (Figure 3-2) were smaller than those in 2010 (Figure 3-4).

The GLM modeling also found a positive relationship between large-fish density and water temperature. The temperature averaged 2°C warmer in 2009 than in 2010 (Table 3-3). Thus, it was hypothesized that 2009 also supported a greater predator density than 2010. In theory, when the BAFF was turned on in 2009, more predators were at the HOR study area to use the BAFF to improve prey encounter rate or capture probability. Furthermore, because it was, on average, 2°C warmer in 2009, there would have been increased energetic demand per predator and greater total energetic demand (see also Appendix H, "Illustrative Example of Striped Bass Predation Using Bioenergetics Modeling"). These results suggest an area of interesting future inquiry. In addition, tagged juvenile Chinook salmon were smaller in 2009 (Table 5-1); thus, the gape size of a predator needed to eat these fish would be smaller. This would tend to increase the size of the effective predator pool.

For both 2009 and 2010, a portion of the benefit from deterrence was removed by predation. With the BAFF on a range of 30.9 to 31.0% of the tagged juvenile Chinook salmon passing through the HOR study area was eaten. Most of this predation may have taken place after the fish had passed the BAFF in the scour hole and the San Joaquin River downstream offshore areas. However, in 2009, some of this predation could have been caused by BAFF operation itself; the proportion eaten was significantly greater with the BAFF on (0.290) than off (0.138).

7.1.4 2011 No Barrier

In 2011, the discharge magnitudes ranged from 5,000 to 7,500 cfs, far greater than in 2009 or 2010. The 2011 results were also very different, with a mean O_E for tagged juvenile Chinook salmon (0.519) that was similar to the proportion of flow remaining in the San Joaquin River (0.48: Table 3-1). It was concluded that, in a high-discharge year with no barrier, tagged juvenile Chinook salmon entered the San Joaquin River in approximately the same proportion as the fraction of flow.

2009 BAFF Off Compared To 2010 BAFF Off Compared To 2011 No Barrier

In 2009 with the BAFF off, many flow reversals in the San Joaquin River (Figure 3-2) led to flow lines routinely moving toward Old River (Figure 3-9), and the population proportion eaten at the HOR study area with the BAFF off was estimated to be 16.4% that year (Table 6-49). In 2010 with the BAFF off, positive discharges always occurred, but the ACVs were intermediate compared to 2011 ACVs, and the population proportion eaten was estimated to be 20.5% (Table 6-50). In contrast, in 2011, high discharges led to the highest ACVs measured during the entire study, with flow lines more toward the San Joaquin River (Figure 3-11); the measured population proportion eaten was 10.1% (Table 6-53).

These discharge and predation patterns resulted in the pattern of O_E (Table 6-32). It was concluded that the effect of the BAFF infrastructure during BAFF off conditions could not be discerned from these data because of the confounding effects of differing environmental conditions, principally discharge, between years.

CHINOOK SALMON COMPARED TO STEELHEAD

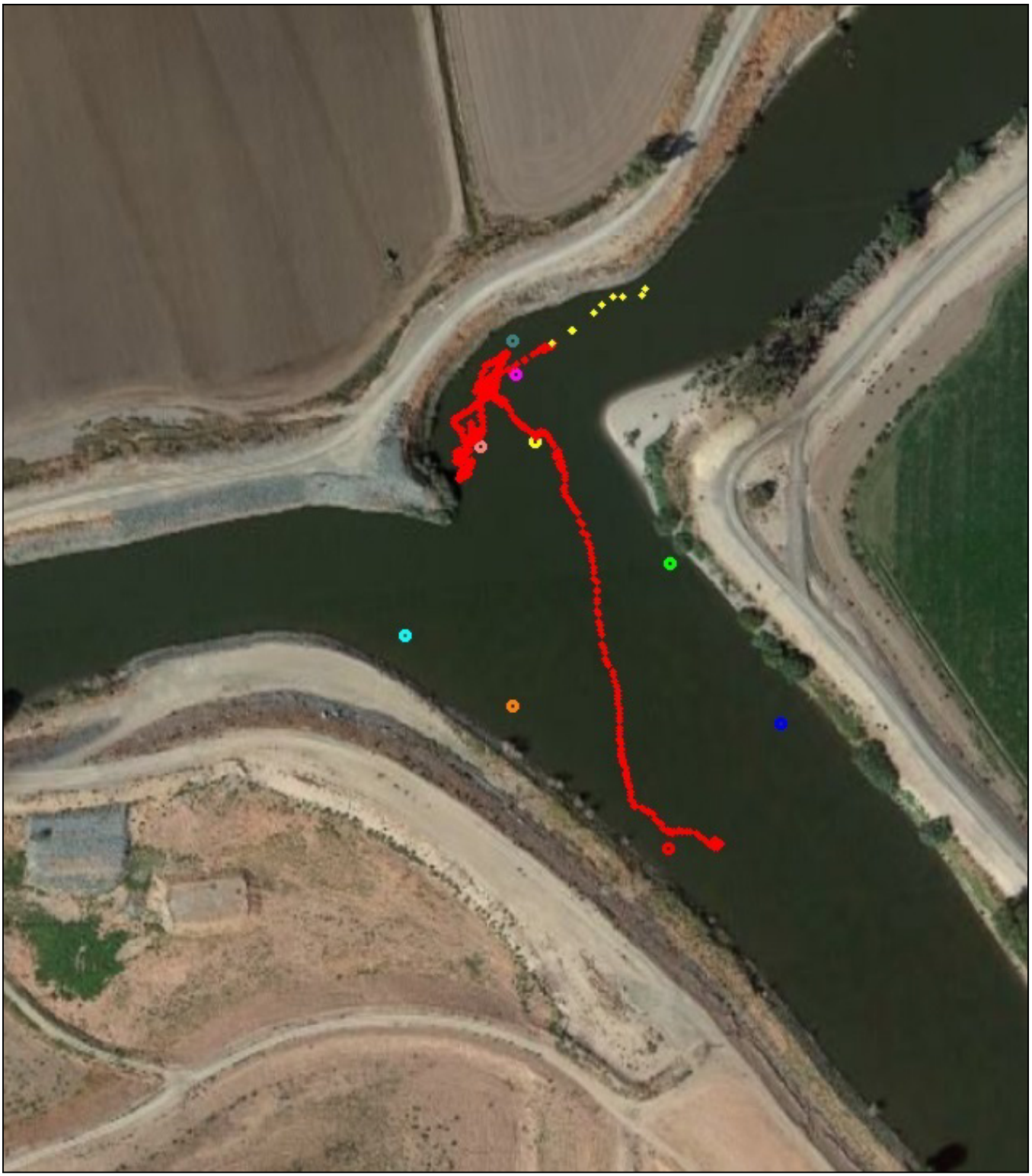
In 2011, tagged juvenile Chinook salmon seemed to enter the San Joaquin River in approximately the same proportion as the fraction of flow. By contrast, steelhead appeared to be less likely than juvenile Chinook salmon to enter the San Joaquin River. However, when tags that were determined to have been eaten were removed, the P_E was not different between tagged juvenile Chinook salmon and steelhead. This suggests that steelhead, like tagged juvenile Chinook salmon, remained in the San Joaquin River in a proportion that was approximately the same as the fraction of the flow.

In 2011, tagged juvenile steelhead appeared to be subject to predation at a higher rate than tagged juvenile Chinook salmon (Table 6-54). However, some of the tags originally inserted into steelhead that were deemed eaten possibly were not eaten. The possibility that steelhead were more likely to receive an incorrect eaten determination than were tagged juvenile Chinook salmon evolved from the steelhead released at Durham Ferry by the Six-Year Steelhead Study/VAMP team and detected at the CVP and SWP holding tanks (see Appendix E, "Fish Fate Determination Guidelines," for discussion). From these steelhead juveniles it was learned that steelhead at the HOR study area sometimes exhibited looping behavior or swam against the flow (Figure 7-2), behavior that also was used as a criterion for determining predation on tagged juvenile Chinook salmon.

For a more accurate understanding of the effects of predation on outmigrating juvenile steelhead in the HOR study area, further research may be required, and alternative methods may need to be developed to distinguish eaten tags. The issue of determining whether a juvenile salmonid has been eaten, for both tagged juvenile Chinook salmon and steelhead, is of prime importance, and is discussed further in Section 8.2.1, "Further Examine Predation Classification."

There did not appear to be any effect on tagged juvenile Chinook salmon or steelhead O_E at different light or velocity levels. However, small sample sizes and low statistical power could have caused an inability to detect any influence. O_E was always higher for tagged juvenile Chinook salmon (13.3 to 17.3 percentage points) than for steelhead, and it was hypothesized in Section 6.1.6, "2011 Chinook Salmon Compared to Steelhead," that steelhead might prefer the Old River route compared to tagged juvenile Chinook salmon.

When tags that had been eaten were removed, no statistical difference was shown between P_E for tagged juvenile Chinook salmon and for steelhead at any light or velocity levels. Thus, the pattern seen in P_E was consistent across all examined light and velocity conditions. However, small sample sizes and low statistical power could have made it impossible to resolve a true difference caused by light or velocity.



Note: Steelhead 5171.04 entered the HOR study area on June 1, 2011, at 11:17 a.m., departed the same day at 11:43 a.m., and was determined to have not been eaten; this determination was confirmed because 5171.04 was later detected at an export facility's holding tank.

Source: Data compiled by Hydroacoustic Technology Inc. this study.

Figure 7-2 **Tagged Juvenile Steelhead Number 5171.04 2D Track in the Vicinity of the Head of Old River Study Area**

7.1.5 2012 PHYSICAL ROCK BARRIER

For tagged juvenile Chinook salmon, the physical rock barrier's O_E was 61.8%. When tags eaten were removed, the rock barrier's P_E was 100%.

The proportion of flow that went down the San Joaquin River in 2012 was 0.82. Eight culverts were installed for the first time in a rock barrier at the HOR study area. Even with eight culverts, however, the proportion of flow entering Old River was relatively low because the rock barrier physically blocked much of the flow.

Of the tagged juvenile Chinook salmon in 2012, a mean of 38.2% were classified as having been eaten in the sample proportion eaten determination (Table 6-55). This was the highest proportion eaten in all four years of study, although no statistically significant difference existed between 2012 and 2009 and 2010 with the BAFF on (2009: 29.0%; 2010: 21.7%), whereas the 2012 proportion eaten was significantly higher than the 2011 proportion eaten (8.7%).

Tagged juvenile Chinook salmon may have been more vulnerable to predation in 2012 than in other years because of eddies that formed near the rock barrier (Figure 3-18). Additionally, a higher density of large fish (greater than 30 cm TL) occurred in 2012 than in 2011. Large-fish density in 2012 increased after the physical rock barrier was installed, during higher water temperatures (see Appendix G, "Plots of Environmental Variables and Large-Fish Density from Mobile Hydroacoustic Surveys," Figure G-6). Thus, the high density of large fish in 2012 may have been caused, in part, by the rock barrier's role in creating more favorable habitat for predation, coupled with more predatory fish moving into the area as water temperatures increased. Additional discussion is provided in Section 7.2, "Predation on Juvenile Salmonids Including Barrier Effects."

7.2 PREDATION ON JUVENILE SALMONIDS INCLUDING BARRIER EFFECTS

This section focuses on the results of the probability of predation analyses as investigated using GLM. The results of the univariate analyses related to proportion eaten are discussed in Section 7.1, "Juvenile Salmonid Routing Including Barrier Effects," because they are closely related to calculations and analysis of O_E and P_E.

Based on the GLM, the present study found the best support for light level, barrier status, and turbidity as predictors of predation probability on tagged juvenile Chinook salmon in the HOR study area. Light level was important in the GLM for 2009/2010/2012 and 2011/2012; because light level was positively related to predation probability, this supported the hypothesis that visual-feeding predators (such as striped bass and largemouth bass) would have lower predation rates in darkness. Examination of the raw data shows that the proportion of tagged juvenile Chinook salmon entering the HOR study area that were preyed upon by day was two to four times greater than the proportion preyed upon at night (Tables 6-58 and 7-1).

The negative relationship between turbidity and predation probability for the 2011/2012 GLM also agrees with greater predation rate with better visibility, as hypothesized based on observed relationships in the Delta (Ferrari et al. 2013). Turbidity is not as highly correlated with discharge (e.g., to the extent that velocity is). Nevertheless, turbidity is higher with greater discharge, and thus, it reflects to some degree the importance of discharge as a master variable that may influence predation.

Table 7-1
Number and Population Proportion Eaten of Tagged Juvenile Chinook Salmon Preyed Upon at the HOR Study Area, 2009–2012

Year/Barrier/Light	Number of Juveniles		Predation	
	Total	Predation	Proportion	Standard Error
2009	525	120	0.229	0.018
a. NPB Off	292	48	0.164	0.022
i. dark	59	3	0.051	0.029
ii. light	233	45	0.193	0.026
b. NPB On	233	72	0.309	0.030
i. dark	45	6	0.133	0.051
ii. light	188	66	0.351	0.035
2010	451	117	0.259	0.021
a. NPB Off	219	45	0.205	0.027
i. dark	77	11	0.143	0.040
ii. light	142	34	0.239	0.036
b. NPB On	232	72	0.310	0.030
i. dark	60	4	0.067	0.032
ii. light	172	68	0.395	0.037
No Barrier (2011)	1,075	109	0.101	0.009
a. dark	306	9	0.029	0.010
b. light	769	100	0.130	0.012
Rock Barrier (2012)	193	76	0.394	0.035
a. dark	38	6	0.158	0.059
b. light	155	70	0.452	0.040
Total	**2,244**	**422**	**0.188**	**0.008**

Notes: NPB = non-physical barrier (bio-acoustic fish fence); Dark <5.4 lux, light ≥5.4 lux
Source: Present study

Turbidity was not found to be a well-supported predictor of predation probability for the 2009/2010/2012 data, which was in agreement with the absence of a statistically important univariate relationship between proportion eaten and turbidity when using groups of juveniles combined across all years (See "Temperature and Turbidity Effects on Proportion Eaten" in Section 6.2.1, "Proportion Eaten [Univariate Analyses]."") The years 2011 and 2012 may have offered sufficient contrast in turbidity to detect the relationship of this variable to predation, and this may have been masked when including the other years.

Discharge alone was not supported as an important predictor of predation probability at the HOR study area. This finding is consistent with a recent study that related discharge to the survival of tagged juvenile Chinook salmon in the Delta (Zeug and Cavallo 2013), but not consistent with the results of other studies (Newman 2010; Perry 2010). To some extent, this may reflect difficulties in assigning a particular discharge to each juvenile for the GLM analysis; the present study used the nearest 15-minute discharge reading from the San Joaquin River at

Lathrop (SJL) gauge at the time when the juvenile track was nearest the 2009 or 2010 BAFF alignments. For variables such as discharge, which may change more rapidly in tidal situations, this means of assigning a discharge value to each juvenile's fate may cause the conditions relevant to predation to differ from those included in the analysis.

Other predictors that change less rapidly (e.g., light level, turbidity) may be more reflective of the conditions experienced by juveniles at the time of predation. However, although water temperature changes would be less rapid, this predictor was not found to be an important predictor of predation probability. The univariate analysis using data from all years did give a statistically significant positive correlation between water temperature and proportion of juveniles eaten. (See "Temperature and Turbidity Effects on Proportion Eaten" in Section 6.2.1, "Proportion Eaten [Univariate Analyses]."") This could be explained by the increased bioenergetics requirements of predators and possibly the greater ability of predatory fish to swim faster in warmer waters compared to tagged juvenile Chinook salmon.

At the broader, annual scale, the predation rate of tagged juvenile Chinook salmon at the HOR study area was appreciably less in 2011 (0.10) than in the other years (0.23 to 0.39). To some degree, this finding likely was related to discharge and its effect on other abiotic and biotic factors (e.g., density of predatory fishes). (See Section 7.3.3, "Changes in Density of Predatory Fishes." Also see the comments in "Comparison of 2009 BAFF Off, 2010 BAFF Off, and 2011 Conditions" in Section 6.2.1, "Proportion Eaten [Univariate Analyses]," about potential mechanisms for differences between years in the proportion of juveniles eaten.) However, despite considerably higher discharge in 2011 than 2010, the overall through-Delta survival of tagged juvenile Chinook salmon released in the San Joaquin River in 2011 (0.02, i.e., 2%) (SJRGA 2013) was not greater than survival in 2010 (0.05, i.e., 5%) (SJRGA 2011). This latter finding could suggest that in 2011, the relatively intense rates of predation observed in 2010 occurred in areas farther downstream where tidal influence was greater (Cavallo et al. 2013). This topic is revisited in Section 8.2.4, "Study Effects of Physical Barriers on Location of Predation Hotspots", in Section 8, "Recommendations."

Barrier status was found to be a well-supported predictor of predation probability for tagged juvenile Chinook salmon in the analysis comparing the non-physical BAFF on/off from 2009/2010 and the physical rock barrier in 2012. Predation probability was appreciably higher with the non-physical barrier turned on or with the rock barrier than with the non-physical barrier off. The analysis did not aim to differentiate between the 2009 and 2010 barrier configurations; still, a reexamination of the basic proportional predation data subdivided by year gives confidence to the conclusion that the results were reasonably consistent for both years of the BAFF deployment (Table 7-1).

In both 2009 and 2010, approximately 0.31 (i.e., 31%) of tagged juvenile Chinook salmon were preyed on with the non-physical BAFF barrier on, compared to 0.16 (2009) and 0.21 (2010) off. Pairwise, statistical comparisons of the proportion eaten using groups of juvenile Chinook salmon found differences between BAFF on and off conditions in 2009, but not in 2010; no substantial difference existed between years in the proportion eaten when the BAFF was on or off. (See "2009 Results," "2010 Results," and "2009 Compared to 2010" in Section 6.2.1, "Proportion Eaten [Univariate Analyses]."")

The higher proportion of predation in light conditions than in the dark also was consistent between years (Table 7-1). Operation of the BAFF has been shown to have some efficacy in deterring juveniles from entering Old River (see "Deterrence Efficiency" in Section 6.1.1, "2009 Results," and Section 6.1.2, "2010 Results"). The

results of the present study suggest, however, that a tagged juvenile Chinook salmon has as high a probability of being preyed upon when the BAFF is operational compared to when the physical rock barrier is installed. This may be the case because juveniles have longer travel distances through the HOR study area as they avoid the noxious stimuli of the BAFF and may be disoriented by the stimuli, or because they are entrained into the eddies that are created by the rock barrier (Johnston, pers. comm., 2013) (see Section 3.2, "Velocity Field"). The transit speed of tagged juvenile Chinook salmon through the HOR study area was greater with the BAFF on than off in 2009 (but not in 2010; see Appendix D, "Transit Speed Analyses," Tables D-4 and D-6). This finding would support the hypothesis that longer travel distance and speed influence predation rate. Anderson et al. (2005) concluded that survival of juvenile salmon in the Snake River depends more on travel distance than travel time or migration velocity. Deterrence away from Old River to the scour hole also may increase predation probability at the HOR study area with the BAFF turned on or with the physical rock barrier installed. The scour hole was one area where the density and occurrence of predatory fish were relatively high, based on the 2011/2012 mobile hydroacoustic surveys and the occurrence of tagged predatory fish (see discussion in Section 7.3.2, "Areas Occupied by Predatory Fishes").

The fit of the binomial GLMs of predation probability (area under receiver operating characteristic [ROC] = 0.70, 0.73) in the present study was within the range of acceptability based on the criteria of Hosmer and Lemeshow (2000). The fit was somewhat better than the fit from a study predicting the presence of Chinook salmon fry in the American River as a function of velocity, depth, substrate, and cover (Beakes et al. 2012); those authors described their model fit (area under ROC = 0.65) as fair predictive ability. By contrast, the GLMs from the present study fit the data considerably less well than the GLMs used to predict the probability of tagged juvenile Chinook salmon entering Georgiana Slough from the Sacramento River, as a function of the operation of the BAFF and other factors (area under ROC = 0.93, "excellent ability to predict fates" [Perry et al. 2012]). The response data (predation) from the present study include some uncertainty because it is not known whether predation actually occurred. Classifying predation was challenging in 2012. Discharge conditions and the physical rock barrier produced juvenile movement patterns that were unlike those seen in previous years (Johnston, pers. comm., 2013).

As noted previously, some difficulty existed in temporally matching the most relevant periods for abiotic predictor variables to juveniles entering the HOR study area. The closest 15-minute readings were used in the present study. Longer averaging periods also would be possible, which may reduce variability (e.g., averages of readings 30 to 60 minutes before and after). The biotic predictor variables representing the potential abundance of predators and abundance of alternative prey—large-fish density from mobile hydroacoustics and small-fish density from Mossdale trawling, respectively—had longer averaging periods than would have been ideal to avoid reducing the sample size of juvenile-response data because of missing values. A better situation would have been to include data specific to the HOR study area that co-occurred more directly in time and space with each juvenile's arrival.

Despite these shortcomings, the statistical analyses of predation probability for tagged juvenile Chinook salmon provided some insights that supported the initial hypotheses. This was not the case for the tagged juvenile steelhead, for which model fits were poor and no better than intercept-only models. Assigning fates to juvenile steelhead was very difficult because their movement patterns were quite different from those of juvenile Chinook salmon (e.g., steelhead holding behavior and upstream movement was reminiscent of movements by tagged

predatory fish [Johnston, pers. comm., 2013]). Further research into means of determining predation is warranted, and this topic is discussed further in Section 8.2.1, "Further Examine Predation Classification."

Bioenergetics modeling conducted as an ancillary part of this study illustrated the relative differences in prey-fish consumption rates between striped bass of different sizes at water temperatures observed at the HOR study area in 2011 and 2012 (Appendix H, "Illustrative Example of Striped Bass Predation Using Bioenergetics Modeling"). The illustrative example of potential consumption rate for prey fish entering the HOR study area produced estimates of predation that were of similar magnitude to the predation estimates for tagged juvenile Chinook salmon in 2012. However, the bioenergetics-derived estimates for 2011 were appreciably lower than the estimates for tagged fish. The relative difference between years (i.e., higher predation in 2012 than in 2011) from bioenergetics modeling was consistent with estimates from the studies of tagged juvenile salmonids, and reflected higher predator density, higher water temperature, and lower prey-fish biomass in 2012. Although illustrative and subject to appreciable uncertainty, the results of the bioenergetics modeling suggested that the rates of predation estimated at the HOR study area from the studies of juvenile salmonid survival may be plausible.

The findings of this study regarding barrier status and its association with predation have clear management implications, particularly when compared to recent studies of the relative survival of tagged juvenile Chinook salmon through the Old River and San Joaquin River routes (Buchanan et al. 2013). This topic is discussed further in Chapter 8, "Recommendations." (In particular, see Section 8.1.1, "Study the Cost-Benefit of Barriers in Relation to Alternative [Non-engineering] Management Strategies," and Section 8.1.3, "Investigate Physical Barrier Alternatives to the Rock Barrier and BAFF.")

7.3 BEHAVIOR AND DENSITY CHANGES IN PREDATORY FISHES

In the following discussion of the results of the evaluation of behavior and density changes in predatory fish at the HOR study area, the results from the study's main elements (tagged predators and mobile hydroacoustics) are considered together. This discussion emphasizes these elements' main findings with respect to several topics of management importance regarding predatory fish at the HOR study area: residence time, areas occupied, and changes in density.

7.3.1 RESIDENCE TIME OF PREDATORY FISHES

The time spent at the HOR study area by tagged predatory fish varied. Generally, however, channel catfish, white catfish, and largemouth bass spent appreciably longer amounts of time overall than striped bass. Variability existed both within and among species.

In other Delta studies, tagged white catfish mostly have been recaptured close to the original site of capture (Moyle 2002). Largemouth bass adults may remain or may wander more widely (Moyle 2002). Nearly all of the largemouth bass that left the HOR study area moved downstream. Studies of channel catfish in the lower Wisconsin River found that they occupied small home ranges in summer, migrated downstream in fall, and migrated upstream to spawn in spring (Pellett et al. 1998). Consistent with these studies, three of the four tagged channel catfish moving from the HOR study area moved upstream in the San Joaquin River.

The residence time of striped bass at discrete areas in the Delta has been the subject of several studies. One study for which the basic data can be summarized in a similar manner to the present study is the 2011 Georgiana Slough Non-

physical Barrier Study (DWR 2012). In that study, which also included spotted bass and Sacramento pikeminnow (not discussed here), 35 acoustically tagged striped bass were detected by the acoustic array near the divergence of Georgiana Slough from the Sacramento River on one to five dates after tagging. The mean percentage of dates when the fish were detected between tagging and deactivation of the acoustic array was 8% (in a range of 2% to 27%), which is comparable to the rates observed in the present study. Miranda et al. (2010) described little fidelity of six tagged adult striped bass within the State Water Project's Horseshoe Bend fish-salvage release site, as fish were detected on one to three dates after tagging. Gingras and McGee (1997) found that the flux of striped bass into or out of Clifton Court Forebay was appreciable; 0 to 100% (mean 17%) of weekly fish movements at the forebay were through the radial gates, as opposed to other parts of the forebay.

The length of time that striped bass spent at the HOR study area before capture and tagging is unknown, although the two striped bass (tag codes 2024 and 2976) that were captured and tagged outside of the study area in 2010 spent short durations (0.5 to 0.6 hour) at the site. These short durations were similar for many of the fish captured and tagged at the HOR study area.

Most movement of striped bass out of the HOR study area (indicated by zone of last detection) was downstream in the San Joaquin or Old rivers. Vogel (2011) described the movements of 24 striped bass tagged and released at the Tracy Fish Facility in spring 2010 that were detected elsewhere in the Delta. Of these, 13 moved downstream to Chipps Island, four moved into various south Delta locations and were last detected in Clifton Court Forebay, four moved north in Old River, two moved upstream to Mossdale via the HOR study area, and one moved to the San Joaquin Deep Water Ship Channel via Old River. This is consistent with a predominantly downstream migration from the south Delta.

Tagged sub-adult striped bass (n = 99) studied by LeDoux-Bloom (2012) showed three main migratory strategies: (1) bay residency; (2) residency in the low-salinity zone; and (3) riverine residency. The riverine resident fish spent summer in the Sacramento and American rivers before migrating downstream to the south Delta (Clifton Court Forebay) in fall, then returned back upstream to the Sacramento and American rivers in the spring to again spend the summer before the fall downstream migration. Adult striped bass generally migrate upstream in spring to spawn, with optimum water temperatures being 15 to 20°C, with no spawning occurring outside the range of 14° to 21°C (Moyle 2002). In 2011, the optimum water temperature range occurred during most of April, May, and June based on water temperatures recorded at the SJL gauge. Most striped bass spawning in the San Joaquin River are found downstream of the HOR study area because of water quality issues (Moyle 2002), but the range extends farther upstream in wetter years, and some striped bass migrating downstream in 2011 possibly had spawned upstream of the HOR study area.

The present study's results indicate that the turnover of striped bass generally is appreciable, with most fish spending a limited amount of time within the HOR study area. Although the residence time of the other predatory fish species is longer, turnover is apparently considerable. Cavallo et al. (2013) conducted a predator removal effort on a 1.6-km reach of the North Fork Mokelumne River on May 19, 2010, and collected an estimated 91% (i.e., 144 of 158) of predatory fish that were vulnerable to electrofishing; 6 days later, a similar effort yielded 83% (i.e., 497 of 601) of predatory fish. The most abundant of these fish were redear sunfish (*Lepomis microlphus*), largemouth bass, bluegill, redeye bass (*Micropterus coosae*), and spotted bass (*Micropterus punctulatus*), with only 10 striped bass collected on both dates. This shows that turnover may be substantial in species other than striped bass. Cavallo et al. (2013) noted:

> While mechanisms are unclear, removal of a stable predator community accomplished in the first treatment was apparently undone within one week by an influx of new predators. If site-specific predator removals are to benefit juvenile salmon survival, sustained effort over time (with daily rather than weekly removals) may be necessary.

The issue of the intensity of predator relocation efforts is discussed further in Section 8.2.3, "Conduct a Pilot Predatory Fish Relocation Study," in Section 8, "Recommendations."

7.3.2 AREAS OCCUPIED BY PREDATORY FISHES

The present study confirms the importance of the scour hole at the HOR study area as an important area for occupancy by predatory fish, as previously suggested on a regional scale from many detections of stationary tags at that location (Vogel 2007, 2010; as cited by SJRGA 2011). One of the reference sites used for comparison to the fish-salvage release sites at Horseshoe Bend (Sacramento River) included a deep hole that harbored high densities of fish (Miranda et al. 2010), as observed in the present study at the HOR study area.

Tagged predatory fish often were found occupying portions of the HOR study area in the San Joaquin River downstream of the Old River divergence, both at the scour hole and in the immediately adjacent areas. To some extent, the areas occupied by tagged predatory fish during the present study reflect the location of release. In this regard, the three white catfish that spent almost all of their time at the scour hole in 2011 were captured, tagged, and released at the scour hole. They remained very close to where they were released, which is not uncommon for the species (see previous comments; Moyle 2002). Capture and tagging crews often found the scour hole to be a profitable place for fishing, although standardized fishing was not undertaken to compare capture rates at the scour hole with other areas. Standardized hook-and-line fishing was conducted at the HOR study area in spring 2013 (Kennedy, pers. comm., 2013). The results, currently being evaluated, will provide data to compare capture rates of predatory fish at the scour hole and vicinity.

Some differences existed in the areas occupied by the different species of tagged predatory fish. For example, striped bass generally were found more often in areas away from shore, although they also occurred nearshore; by contrast, largemouth bass tended to occur more in the nearshore zones. (The index of zone use relative to zone size emphasized the relatively frequent use of nearshore zones.) Such findings reflect differences in the biology of the species, with largemouth bass tending to be more structure-oriented inhabitants of lower-velocity areas (Stuber et al. 1982), and striped bass being pelagic (Moyle 2002). Channel catfish were found more in offshore areas, which may indicate their movement into somewhat faster water to feed, although areas with cover also were important (Moyle 2002). The aforementioned occurrence of white catfish in the scour hole for much of the time was in keeping with aggregation in deeper parts of the channel for this species (Moyle 2002).

The analysis of velocities occupied by tagged predatory fish confirmed the main patterns shown by the spatial analysis of the areas occupied. Catfish and largemouth bass occupied areas with estimated near-surface velocities that were very low in comparison to all velocities available at the HOR study area. Largemouth bass is the only focal predatory fish species from the present study with a published habitat suitability index for velocity. That suitability index is expressed as average summer-current velocity at 0.6 of water depth and ranges from optimal (index = 1) at zero to 0.06 m/s, before a steep decline to zero at 0.2 m/s (Stuber et al. 1982). The results of the present study were in agreement with this index; largemouth bass rarely were found in waters with estimated near-surface velocity of 0.1 m/s or more. Near-surface velocity is not truly representative of velocity in the

demersal habitats occupied by catfishes or largemouth bass, but it may still provide an index of velocity differences at greater depths.

Striped bass was different from the other predatory fish in that it occupied a wide range of velocities. Some individuals had median occupation velocities greater than the median velocities available at the HOR study area. As noted previously, this reflects the species' pelagic nature and occupation of a variety of habitats.

Down-looking mobile hydroacoustic surveys showed an extremely high concentration of fish in the scour hole, whereas side-looking hydroacoustic surveys showed many fish at that location, but also appreciable numbers in other areas. This probably reflects a combination of fish distribution and sampling efficiency. The spread of the down-looking beam is less in shallow areas than in deeper areas, so a greater likelihood to detect fish in deeper areas such as the scour hole may be possible. By contrast, the side-looking beam does not have this issue, and generally samples over a greater range. It was nevertheless apparent from side-looking mobile hydroacoustics that the scour hole and the area just upstream were areas of high fish density.

This study assumed that mobile hydroacoustic surveys reasonably indicate changes in the abundance of large-bodied predatory fish at the HOR study area, although the proportion of predatory fish versus non-predatory fish was unknown. Considerable aggregations of common carp were observed visually near the 2012 HOR physical rock barrier. Many of the large-bodied fish observed with down-looking mobile hydroacoustics also may have been common carp; the analysis of fish depth relative to water column depth found that many fish remained close to the substrate at all times of the day. Such a pattern would be consistent with a primarily demersal, benthic-feeding fish such as common carp (Moyle 2002). Catfish, one of the focal predatory fish from the present study, also are primarily demersal (Moyle 2002).

Stationary tags (thought to be from juvenile salmonids that had been preyed upon) provided a third source of information about areas occupied by predators. These tags also indicated the considerable importance of the scour hole and vicinity, because most stationary tags were found there, with very few stationary tags found elsewhere. The acoustic arrays at the HOR in the present study allowed the locations of stationary tags to be determined more precisely than the mobile surveys undertaken as part of the VAMP studies (SJRGA 2010, 2011, 2013). In the present study, one stationary tag from a tagged juvenile Chinook salmon was found immediately adjacent to the downstream side of the 2012 physical rock barrier (another was found farther downstream in Old River), suggesting that the near-barrier area was occupied by predatory fish. These two stationary tags suggest that the only two juveniles entering Old River through the culverts of the 2012 physical rock barrier were preyed upon, based on the detection data. Previous studies have found stationary tags close to other barriers, as with those that were installed as part of the Temporary Barriers Project (Vogel 2010, as cited by SJRGA 2010).

In the present study, tagged largemouth bass that were released downstream of the 2012 physical rock barrier were detected at the barrier bottom or within 5 m of the barrier much of the time. Detection of these largemouth bass indicated a tendency by these fish to remain at or close to the barrier, and therefore, to potentially pose a predation threat to any fish passing through the barrier's culverts. The single largemouth bass tagged in 2009 spent an appreciable amount of time (nearly 50% of all detections) within 5 m of the 2009 BAFF at the upstream end, closest to shore. Little evidence existed of striped bass spending much time close to the 2009/2010 BAFF, although the number of tagged fish during these years was very low (n = 4).

The main importance of the present study's results is that the scour hole was confirmed as an area of high predator occupation. Areas adjacent to the scour hole also were found to be important for predatory fish, and species-specific differences existed in habitat use (e.g., nearshore/offshore). Also, the barrier treatments (particularly the 2012 physical rock barrier) were apparently somewhat important as a location for predatory fish. These findings have important implications for limiting predator abundance at the HOR study area, whether through direct means (capture/relocation) or through indirect means (habitat manipulation, such as scour hole filling). This is discussed further in Section 8.2.2, "Study Feasibility of Physical Habitat Reconfiguration," and Section 8.2.3, "Conduct a Pilot Predatory Fish Relocation Study," in Section 8, "Recommendations."

7.3.3 CHANGES IN DENSITY OF PREDATORY FISHES

The main environmental predictors associated with changes in the density of large fish (greater than 30 cm TL) from both down-looking and side-looking mobile hydroacoustic surveys were same-day discharge and water temperature. Large-fish density increased as discharge decreased and water temperature increased. To some extent, this reflected differences both between and within years. The density of large fish was considerably less in 2011 than in 2012; discharge was considerably higher in 2011 than in 2012. The lower density of large fish in 2011, presumably including many predatory fish, may reflect lower habitat suitability with higher velocity, as has been described for largemouth bass (Stuber et al. 1982). The 2012 surveys provided a contrast between very low abundance during March, which had low water temperatures (approximately 12° to 15°C), and higher abundance in May (18° to 22°C). This suggests seasonal migration to and through the HOR study area by large fish, such as striped bass that spawn during spring.

The results found little evidence for much importance of other predictors of large-fish density. However, in relation to the predictor of small-fish abundance (from Mossdale trawling), which was taken to be a measure of potential prey abundance in the general area, the extent to which upstream trawling would provide an indication of small-fish abundance at the HOR study area is unknown. Nevertheless, pulses of fish in Mossdale trawls generally were followed by pulses of fish at the south Delta's salvage facilities (Jones & Stokes 2007). Therefore, the issue may be more of a temporal mismatch (i.e., 3-day mean small-fish density is not necessarily representative of the density of small fish at the time of the mobile hydroacoustic surveys).

Considerable noise in the water column (e.g., from suspended, non-fish materials being washed downstream) precluded using the hydroacoustic surveys to estimate the density of small fish at the HOR study area. In addition, and as discussed briefly in Section 7.3.2, "Areas Occupied by Predatory Fishes," a difficulty in interpreting data from mobile hydroacoustic surveys existed because the proportion of large fish actually consisting of predatory fish was unknown.

The density of large fish at the HOR study area was either greater than or not substantially different from the density of large fish at the reference sites. In addition, although density estimates were quite variable at all sites, important correlations existed between the HOR study area and the reference sites in approximately half of the comparisons. Taken together, these results suggest that wide-ranging factors (e.g., discharge and water temperature) affect fish density over much of the San Joaquin River, and that the HOR study area has a relatively high density of large fish compared to other sites. As noted previously, the scour hole at the HOR study area was found to be a hotspot of predation in some years, based on stationary tag detections (Vogel 2007, 2010; as cited by SJRGA 2010).

In more recent years, other locations farther downstream in the San Joaquin River and Grant Line Canal have had greater concentrations of stationary tags (SJRGA 2011, 2013), suggesting that more intense predation occurs at those locations. Indeed, SJRGA (2011 2013) noted that "predation did not appear to be a problem near the Head of Old River" in 2010 and 2011 based on the relative density of stationary tags. As described in Section 7.2, "Predation on Juvenile Salmonids, Including Barrier Effects," predation at the HOR study area was lower in 2011 than in the other years, but predation in 2009 and 2010 during BAFF operations was comparable to predation in 2012 (and overall appeared somewhat high, with predation of more than 30% of juveniles entering the area). This study's findings of discharge- and water temperature-related differences in the density of large fish and relatively high large-fish density compared to other areas of the San Joaquin River have implications in terms of prioritizing predator management efforts at the HOR study area, both temporally (within and between years) and spatially (at which location). These implications are discussed further in Appendix J, "Recommended Aspects of a Pilot Predatory Fish Relocation Study," and Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan" (see Section K.2, "Predation Reduction").

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8 RECOMMENDATIONS

8.1 JUVENILE SALMONID ROUTING INCLUDING BARRIER EFFECTS

8.1.1 STUDY THE COST-BENEFIT OF BARRIERS IN RELATION TO ALTERNATIVE (NONENGINEERING) MANAGEMENT STRATEGIES

The present study showed that non-physical (BAFF) and physical (rock) barriers had varying levels of effectiveness in influencing juvenile salmonid routing at the HOR study area. No option that was studied provided overall efficiency (O_E) greater than 62% and a population proportion eaten less than 30 % (Table 8-1). The O_E result provided herein does not depend upon classification of salmonid juvenile fate from 2D tracks. (Note that there is some uncertainty about classification of salmonid juvenile fate, and this is recommended for further study; see Section 8.2.1, "Further Examine Predation Classification").

Table 8-1
Summary of Statistics for Tagged Juvenile Chinook Salmon Released, 2009–2012

Year/Treatment	Overall Efficiency	Protection Efficiency	Proportion Eaten at Study Area	Proportion Never Arrived at Study Area	Mean Water Temperature (°C)[1]	Mean Discharge (cfs)[1]
2009 BAFF on	0.209	0.338	0.309	0.446[2]	18.6	864
2010 BAFF on	0.355	0.441	0.310	0.112[2]	16.4	2,646
2011 no barrier	0.519	0.574	0.101	*	16.6	5,117
2012 rock barrier	0.618	1.000	0.393	0.539	18.9	1,855

Notes: °C = degrees Celsius; BAFF = bio-acoustic fish fence; cfs = cubic feet per second

[1] Water temperature and discharge mean values were calculated from measurements when fish were detected in the Head of Old River study area, and refer to the San Joaquin River at Lathrop gauge.

[2] Proportion Never Arrived was calculated with all tags, rather than only tags that later encountered the BAFF when it was on.

[*] Unknown because only a subset of tags were processed in this year, with the focus on the Head of Old River study area.

Sources: Present study; Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013

Since 2010, the rate of juvenile salmonid survival through the Delta along the San Joaquin River route has been similar to or lower than the survival rate along the Old River route (SJRGA 2011, 2013); previous studies showed that survival was higher along the San Joaquin River route than along the Old River route (see review by Hankin et al. 2010). Lower survival along the San Joaquin River route is contrary to the management goal that a HOR barrier is intending to achieve—less use of the Old River route. However, survival rates are very low along either route, generally less than 10% (SJRGA 2011, 2013; Buchanan et al. 2013). This suggests that conditions in the south Delta are generally poor, particularly compared to through-Delta survival rates for Sacramento River–origin salmonids, 35.1 to 54.3% (Perry et al. 2010). Perry et al. (2013:389) noted that:

> …while shifting the distribution of fish among routes influences overall survival, the magnitude of absolute change in [through-Delta survival] is constrained by the maximum survival observed in any given route. Further increases in [through-Delta survival] require management actions that affect not only migration routing, but also survival within migration routes.

In this light, it is recommended that the cost and benefit of barriers at the HOR study area be studied in relation to the costs and benefits of alternative management strategies, particularly nonengineering solutions such as habitat restoration.

Existing planning efforts are considering the potential for habitat restoration in the south Delta, which could improve the quality of different migration routes. The proposed BDCP contemplates a suite of conservation measures that would restore floodplain habitat, tidally influenced habitat, and channel margin habitat, while enhancing flood control benefits for surrounding areas (see Section K.3, "South Delta Habitat Restoration," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan," of this report). It is recommended that the potential benefits of barrier installation at the HOR study area be considered in light of such efforts. Note that this recommendation is consistent with a recommendation to study physical barriers further (see Section 8.1.3, "Investigate Physical Barrier Alternatives to the Rock Barrier and BAFF"), because the potential benefits of a physical barrier involves both near-field effects (preventing fish from entering an undesirable route, e.g., Old River) and potential far-field effects (retaining flow in the San Joaquin River; see also Section 8.2.4, "Study Effects of Physical Barriers on Location of Predation Hotspots"). The far-field effects may contribute to a potential change in survival along a given route (Perry et al. 2013). The potential to change habitat and directly affect numbers of predatory fish is discussed in Section 8.2.2, "Study Feasibility of Physical Habitat Reconfiguration," and Section 8.2.3, "Conduct a Pilot Predatory Fish Relocation Study."

The potential synergy between nonengineering and engineering strategies therefore is recommended for further study. Barrier installation at the HOR study area may have more value if habitat is improved along the south Delta migration routes.

8.1.2 Conduct Additional Analysis of Existing Data Using Supplementary Techniques

The assessment of juvenile salmonid routing, including barrier effects, was based on a number of univariate analyses that generally tested null hypotheses specified *a priori*. This approach was adopted largely to maintain consistency with previous evaluations at the HOR study area (Bowen et al. 2012; Bowen and Bark 2012). It is recommended that additional analysis of these data be considered using supplementary techniques, such as GLM. The GLM approach was used in the present study's analysis of probability of predation (see Section 7.2, "Predation on Juvenile Salmonids Including Barrier Effects"). Recently this approach was applied to an analysis of the probability of route entrainment at the HOR study area (SJRGA 2013; reproduced in this report as Appendix I, "Route Entrainment Analysis at Head of Old River, 2009 and 2010").

The GLM approach supplements the univariate approach by allowing simultaneous consideration of many environmental variables. In addition, the GLM approach allows consideration of the continuous nature of environmental variables, as opposed to grouping variables (e.g., velocity) by predefined thresholds (as was undertaken with the univariate analyses in the present study). This allows consideration of barrier effects across the range of a given environmental variable. Thus, for example, SJRGA (2013) found that in 2009, below approximately 1,000 cfs (San Joaquin River at Lathrop discharge), there was little difference between BAFF-on and BAFF-off treatments in the probability that juvenile Chinook salmon would remain in the San Joaquin River. In contrast, above a discharge of 1,000 cfs, the probability was appreciably greater with the BAFF on (see Figure 7-1 in Appendix I, "Route Entrainment Analysis at Head of Old River, 2009 and 2010").

The analysis of route entrainment conducted by SJRGA (2013) is analogous to the univariate analysis of protection efficiency (P_E) (i.e., only surviving juvenile Chinook salmon are considered). It is recommended that a GLM analysis be undertaken that is more analogous to the univariate analysis of O_E, i.e., including juveniles that were preyed upon at the HOR study area. This could be done with a GLM based on a trinomial response distribution, for example, with three juvenile Chinook salmon fates ("remained in San Joaquin River," "entered Old River," or "preyed upon").

It is also recommended that additional analyses be undertaken of data collected in 2013 (i.e., from the study similar to the Vernalis Adaptive Management Program's release of tagged juvenile Chinook salmon and from tagged juvenile steelhead released as part of the Six Year Steelhead Study mandated by the NMFS [2009] OCAP BO). Such analyses would allow comparison of juvenile salmonid routing and survival with a low-discharge, no-barrier treatment (i.e., 2013) with the other years (2009–2012) included in the present study.

8.1.3 NVESTIGATE PHYSICAL BARRIER ALTERNATIVES TO THE ROCK BARRIER AND BAFF

Deploying a BAFF at the HOR study area is not recommended at this time, for two main reasons. First, estimated population proportion eaten of juvenile Chinook salmon during BAFF operation in 2009/2010 was very high, at 31%, and predation was not significantly different from predation when the physical rock barrier was installed in 2012, as discussed in Section 7.2, "Predation on Juvenile Salmonids Including Barrier Effects." Second, in 2009, predation was significantly greater with the BAFF on than off.

As described in Section 8.2.1, "Further Examine Predation Classification," there is a need to develop further the methods to classify the fate of tagged juvenile salmonids. Irrespective of this need, even if predation had been overestimated considerably with the BAFF on, the BAFF's influence on routing of juvenile salmonids produced only a modest gain in the proportion of juvenile salmonids remaining in the San Joaquin River (e.g., in 2010, mean P_E of 0.441 with BAFF on versus 0.286 with BAFF off; see also Figures 7-3 and 7-4 of Appendix I, "Route Entrainment Analysis at Head of Old River, 2009 and 2010"). Sample proportion eaten was relatively high with the physical rock barrier (and not significantly different than with the BAFF on); however, the rock barrier eliminated entry into Old River of tagged juvenile Chinook salmon determined to have not been eaten, the primary management goal of the barrier installation (see Protection Efficiency in Table 8-1).

The second reason for not recommending deployment of a BAFF is that recent studies have not found through-Delta survival to be lower for juvenile Chinook salmon entering Old River instead of remaining in the San Joaquin River, in contrast to the situation generally observed historically (Hankin et al. 2010). Indeed, survival along the Old River route has been comparable to or greater than survival along the San Joaquin River route in recent years (SJRGA 2010, 2013; Buchanan et al. 2013). The reasons for this recent change are unknown, although Buchanan et al. (2013: 228) have suggested that "it is possible that the non-physical barrier deprived smolts routed to the San Joaquin River of the increased flows necessary for improved survival." It is recommended that juvenile Chinook salmon survival through the Delta be studied further to assess if evidence persists into the future for the Old River route having higher survival than the San Joaquin River route. Because no long-term route survival data series exists for steelhead, juvenile Chinook salmon survival is the only metric currently available for assessment of the through-Delta success of the Old River route compared to the mainstem San Joaquin River route.

Hankin et al. (2010:27) considered the installation of a physical barrier at the HOR study area to be potentially beneficial because, in addition to the more desirable mainstem San Joaquin River fish routing, it would "ensure that essentially all San Joaquin flow proceeds down the main channel, thereby presumably enhancing (juvenile) smolt survival via a mainstem flow effect." Furthermore, they made the following recommendation (Hankin et al. 2010: 28):

> If an Obermeyer Gate is considered, it should be located near the edge of the hydraulic flow line of the main channel of the San Joaquin River. Data support that in-river structures such as a fill dam, but also bridge abutments, scour holes, piers and pump stations, provide habitat for predators in this reach of the river (Vogel, pers. comm., 2010). The position of the original HORB [Head of Old River Barrier] was set back into the entrance of the channel leading into Old River. This site was chosen most likely for ease and cost to construct and remove. Unfortunately, it also set up hydraulic conditions ideally suited for predators: slack water and cover. If a future barrier at the HOR is constructed, alignment along the San Joaquin embankment would create a higher sweeping velocity down the main channel, would move smolts more swiftly past this location, and should reduce predator habitat.

The results of the present study tend to support the foregoing recommendation of Hankin et al. (2010). Predation at the HOR study area with a physical rock barrier installed may have been relatively high. Population proportion eaten was 39% of tagged juveniles entering the study area, if the estimates of juvenile Chinook salmon eaten are reasonably accurate. This appeared to be at least partly attributable to unfavorable hydraulic conditions, such as eddies generated by the position of the rock barrier. Therefore, it is recommended that the feasibility of physical barrier alternatives be considered for the HOR study area, following the recommendations of Hankin et al. (2010).

Important considerations for the feasibility of a physical barrier include the need to consider water use in Old River (i.e., maintaining adequate water levels for agricultural diversions) and the Old and Middle River flows necessary to limit the potential for delta smelt (and other species of concern) to move toward the south Delta export facilities from the central or west Delta. In addition, locating a physical barrier closer to the San Joaquin River's hydraulic flow line would increase construction and operations/maintenance costs (J. McQuirk, pers. comm., 2013).

Further investigation of the feasibility of a physical barrier at the HOR site would inform the proposal to construct an HOR operable gate under the Bay Delta Conservation Plan (DWR 2013). This is discussed further in Section K.1, "Operable HOR Gate," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan," of this report. Such a gate would obviate the need for a non-physical barrier and may facilitate the types of mainstem San Joaquin River discharge–related benefits suggested by Hankin et al. (2010).

Study of a physical barrier should consider any effects on the potential for changes in delta smelt entrainment at the south Delta export facilities because of changes in Old and Middle river discharges. This could be done at a planning level, for example, by modeling Old and Middle river discharges under different physical barrier configurations. The modeling then could be applied to established relationships between proportional entrainment of larval/juvenile delta smelt and spring (March–June) Old/Middle River discharge and the location of the low-salinity zone (see USFWS 2008:220).

Any study of physical barrier alternatives to the rock barrier and BAFF should consider the timing of barrier installation relative to juvenile salmonids' outmigration periods. Historic installation of the HOR barrier has been tailored to coincide with the spring (April–June) outmigration period of juvenile Chinook salmon in the San Joaquin River watershed, whereas juvenile steelhead outmigration may warrant earlier installation. (For example, the migration period noted for the Stanislaus River at Caswell is January to July, with a peak in March, and moderate abundance from February to June [NMFS 2009: Table 4-6].)

The recommendation to investigate physical barrier alternatives includes a recommendation to consider possible effects of the San Joaquin River Restoration Program (SJRRP). The SJRRP aims to implement the restoration goal of the San Joaquin River Restoration Settlement: "To restore and maintain fish populations in 'good condition' in the main stem of the San Joaquin River below Friant Dam to the confluence of the Merced River, including naturally reproducing and self-sustaining populations of salmon and other fish" (SJRRP 2011).

The SJRRP's actions occur well upstream of the HOR study area. The migration route of spring-run and fall-run Chinook salmon emigrating to or from the restoration area includes the HOR study area. Therefore, management actions at the HOR study area would affect these fish. The timing of fall-run Chinook salmon migration presumably would be similar to that observed elsewhere in the San Joaquin River basin (i.e., primarily juvenile spring outmigration and fall adult immigration). However, the timing of spring-run Chinook salmon may result in new considerations (e.g., with respect to adult spring upstream migration). In addition, depending on the juvenile phenotypes expressed, a broader variety of outmigration timing may exist, with differences between young-of-the-year, fry migrants, and older juveniles that may have reared in-river for over a year. These are considerations for the timing of any barrier operation at the HOR study area, as well as any other associated activities that may be planned (e.g., predator relocation; see Section 8.2.3, "Conduct a Pilot Predatory Fish Relocation Study").

Clearly, the potential exists for any future management activities at the HOR study area to affect migrating salmonids from a restored San Joaquin River above the Merced River confluence. Based on the SJRRP's use of tagging studies to assess juvenile Chinook salmon survival in the watershed above the Merced River confluence (SJRRP 2012), it is recommended that study efforts specific to the HOR study area and the SJRRP be coordinated, to track the same tagged study fish as they pass through the HOR study area. This would be of value because these study fish would have had considerably longer to acclimate to the natural environment by the time they reached the HOR study area, compared to fish released at more typical locations, such as Durham Ferry (e.g., Bowen et al. 2012). Sample sizes may be low, however, because of the losses that may occur between the release sites and the HOR study area. Coordinated efforts may have to significantly increase the number of study fish.

8.2 PREDATION ON JUVENILE SALMONIDS INCLUDING BARRIER EFFECTS

8.2.1 FURTHER EXAMINE PREDATION CLASSIFICATION

With respect to predation, a key uncertainty that warrants further research is the actual fate of tagged juvenile salmonids that have been classified as having been preyed upon or having survived at the HOR study area. The GLM statistical analysis of juvenile Chinook salmon at the HOR study area was successful in supporting some of the *a priori* hypotheses regarding factors affecting juvenile predation (i.e., light level and turbidity), as well as highlighting the fact that predation was greater with the physical rock barrier and BAFF operations than with the BAFF not operating.

However, the GLM analysis for steelhead provided no insight into mechanisms affecting predation. This may be attributable to the difficulty in assigning predation fate. Predation studies of both juvenile Chinook salmon and steelhead would benefit from some means of verifying predation fate, or of developing objective, quantitative criteria to classify predation. An example of this was provided in the 2012 Georgiana Slough Non-physical Barrier Study (DWR in review), which used mixture models to estimate the probability of a track being a predator based on the tortuosity of the track in the study area (Romine et al. 2014). It is recommended that the 2009–2012 data from the HOR study area be examined to determine how fate classification corresponds with classifications from mixture models based on data either from tagged predatory fishes at Georgiana Slough or, preferably, from the tagged predatory fishes from the HOR study area presented in this study.

It is also recommended that predation classification in future studies at the HOR study area (by mixture models, qualitative fate classification, or other means) incorporate the use of the new predation tag. Predation tags are proprietary technology that has been developed by Hydroacoustic Technology, Inc., and for which a patent application is in process. The acoustic signal emitted by predation tags changes sometime after a tagged juvenile salmonid has been preyed upon, thus indicating the fate of the juvenile salmonid. Classification by mixture models or other means can then be compared to the known fate of the predation tag. Therefore predation rules described in Appendix E could be tested as follows: (1) develop 2D tracks for juvenile Chinook salmon before and after known predation events from the predation tag; (2) experts apply human rules described in Appendix E to assign fate; and (3) statistically compare the groups of uneaten, eaten, and unknown from predation-tag known to those for expert human assessments.

The primary limitation to using predation tags is the lag time between the predation event and the change in signal from the predation tag, which may preclude assigning predation by predatory fishes at the HOR study area if these predatory fishes have a relatively short residence time (striped bass). Nevertheless, predation tags appear to hold promise for informing broader-scale survival estimates through the south Delta as a whole. Thus, they would tie in to studies that consider the broader circumstances along the migration route rather than just the HOR study area (see Section 8.1.1, “Study the Cost-Benefit of Barriers in Relation to Alternative [Nonengineering] Management Strategies”).

Transit speed was identified as a quantitative attribute that can assist in classifying predation on juvenile salmonids (see Appendix D, “Transit Speed Analyses”). It is recommended that this attribute be used to aid predation classification in future studies. Tagged juvenile Chinook salmon that were classified as having been preyed upon passed through the HOR study area at a much slower rate than tagged fish that were not eaten.

It is further recommended that the use of transit speed as one criterion for classifying predation also take into account the relationship between discharge, average channel velocity, and transit speed. Individual transit speed should be evaluated as an indicator of predation probability. The individual transit speed should be compared to the mean transit speed for all tags experiencing the same conditions in a specific year. However, because the behavior of steelhead juveniles can appear similar to the behavior of predators, it is recommended that transit speed evaluation be species-specific.

8.2.2 Study Feasibility of Physical Habitat Reconfiguration

The preponderance of stationary acoustic tags for juvenile salmonids in the scour hole and the association of predatory fish with the scour hole and adjacent areas at the HOR study area (see Section 7.3.2, “Areas Occupied

by Predatory Fishes") leads to the recommendation that a study be undertaken regarding modification of the scour hole's bathymetry. Modification could involve filling the scour hole with suitable substrate. Such actions are under consideration in other planning efforts for the Delta, e.g., the Bay Delta Conservation Plan (Section K.2, "Predation Reduction," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan," of this report). Clearly, such action would require a detailed modeling effort to ascertain the potential effects on both the river near the HOR study area and upstream and downstream of the site. Particular consideration would be needed for effects on river banks and levees that could occur as a result of any modification to the scour hole.

8.2.3 CONDUCT A PILOT PREDATORY FISH RELOCATION STUDY

Regardless of the presence or absence of a barrier at the HOR, sufficient evidence is apparent to conclude that predation is considerable at the study area. The present study suggests that the population proportion eaten of juvenile Chinook salmon entering the site has been high in most years (0.23 in 2009, 0.26 in 2010, 0.10 in 2011, and 0.39 in 2012; see Table 7-1 of Section 7.2, "Predation on Juvenile Salmonids Including Barrier Effects", in Section 7, "Discussion"). As noted previously in Section 8.2.1, "Further Examine Predation Classification," there is the need to investigate further the uncertainty about the fates of juvenile salmonids.

Mobile surveys of stationary acoustic tags from dead salmonids have not always shown that the HOR study area and vicinity to be a regional hotspot of predation (SJRGA 2010, 2011, 2013); however, the foregoing rates of predation, assuming that they are reasonably accurate, are of concern. Consideration of relocating predators from the HOR study area and vicinity may be warranted; as described further in Section 8.2.4, "Study Effects of Physical Barriers on Location of Predation Hotspots," identifying the locations of predation hotspots and how they shift seasonally in relation to environmental conditions is valuable, so that efforts to relocate predatory fish could focus on problem areas. Given the scarcity of predator control studies in the Delta (see Grossman et al. 2013) and the proposed use of such actions in planning efforts (see Section K.2, "Predation Reduction," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan"), it is recommended that a pilot predatory fish relocation study be undertaken at the HOR study area.

The feasibility of relocating predators is highly uncertain and problematic, particularly with respect to an open area such as the HOR study area. Gingras and McGee (1997:13) discussed the feasibility of predator control in Clifton Court Forebay, another open system in the Delta, and concluded:

> Because removal efforts at Clifton Court Forebay would not affect reproduction in the striped bass (predator) population or recruitment to Clifton Court Forebay, logic dictates that the level of exploitation to substantially reduce predation at Clifton Court Forebay would need to be very high.
>
> Notwithstanding the extraordinary effort that predator removal would pose as a means to improve prescreen survival of fish entrained at Clifton Court Forebay, a coordinated program to reduce predation should be expected to yield some degree of positive effect. In this respect, initiating a predator control program may seem attractive; however, in a review of 250 fish control projects, Meronek et al. (1996) classified most of them as failures. They documented many proximate causes for failure (e.g., insufficient reduction in numbers) but suggested that unreported "seminal reasons" were more often the cause. Suggested seminal causes of failure were insufficient pre- and post-treatment study and lack of criteria for success. Proposed predator removal activities at Clifton Court Forebay have been delayed in substantial part due to the inability to reach a

consensus on the criteria to quantify success. Because fundamental assumptions of mark/recapture methods for abundance estimation are not valid when Clifton Court Forebay is operated normally, predator control activities would need to be evaluated without accurate predator abundance estimates. Quantifying any improvement in prescreen survival attributable to predator removal efforts would be difficult.

In the only available published Delta study of predator control efforts, a study on the North Fork Mokelumne River, Cavallo et al. (2013) demonstrated that predator removal may be feasible[1]. Electrofishing was used to catch predatory fishes in a 1.6-km impact reach; the survival rates of tagged juvenile Chinook salmon were compared before and after the removal in the impact reach and in an upstream 2-km control reach. Survival was greater than 99% in the reach after the removal, compared to less than 80% before the removal. Survival in the control reach was variable and did not differ before and after the removal. However, survival in the impact reach declined to initial levels after a second predator removal effort, before increasing to very high levels (again greater than 99%) after a considerable increase in discharge caused by the opening of the Delta Cross Channel gates.

Although the results of Cavallo et al. (2013) show predator removal may be challenging, their study serves as a useful template for the type of study that could be considered as a pilot predator relocation effort at the HOR study area. Indeed, the National Marine Fisheries Service's Southwest Fisheries Science Center has commenced study to manipulate predatory fish density at the HOR study area in 2014-2016. This study and any other similar studies would have direct relevance for the proposed BDCP (see Section K.2, "Predation Reduction," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan," of this report).

The results of the present study also have the potential to guide any pilot predator relocation efforts that may be considered, such as by illustrating the areas of greatest predatory fish density (see "Areas Occupied" in Section 6.3.2, "Hydroacoustic Data" of Section 6, "Results"). Features of a pilot predator relocation study are summarized in Appendix J, "Recommended Aspects of a Pilot Predatory Fish Relocation Study." That appendix, as well as Section K.2, "Predation Reduction", of Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan," also discuss how the results of the present study have the power to inform future studies and planning efforts.

8.2.4 Study Effects of Physical Barriers on Location of Predation Hotspots

With respect to the influence of a physical barrier on flow, Cavallo et al. (2013) illustrated that river inflow to the Delta has an important effect on the extent of the channel under appreciable tidal influence (i.e., with bi-directional flows much of the time). They suggested, "If the tidal transition zone occurs where habitat conditions are poor, or where predator densities are high, juvenile salmon are likely to experience greater predation mortality, and perhaps impaired growth. This should be studied more fully."

In relation to the situation at the HOR study area, and to the broader San Joaquin River and south Delta, examining the locations where predation hotspots occur (SJRGA 2010, 2011, 2013) is recommended, to see how they relate to the tidal transition zone. Clearly, deploying a physical barrier would have the potential to influence

[1] Note that Sabal (2014), in her master's thesis work, found that juvenile Chinook salmon survival below Woodbridge Irrigation District Dam on the lower Mokelumne River increased by approximately 25-30% following removal of predatory fishes by electrofishing.

the position of the tidal transition zone and may guide future management efforts, such as predator relocation (see Section 8.2.3, "Conduct a Pilot Predatory Fish Relocation Study," and Section 8.3.2, "Assess Predatory Fish Density in Relation to Predation Hotspots") and the proposal for a physical barrier in the Bay Delta Conservation Plan (Section K.1, "Operable HOR Gate," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan").

In addition, understanding the factors influencing predation hotspots would improve planning of complementary management strategies such as habitat restoration and habitat reconfiguration. (See Section K.2, "Predation Reduction," and Section K.3, "South Delta Restoration," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan.") Therefore it is recommended that the influence of a physical barrier on the location of predation hotspots and the tidal transition zone be studied further to elucidate potential far-field effects of physical barrier installation.

8.2.5 Study Potential Effects of Changing Recreational Fishing Regulations

The results of the present study suggested that predation on juvenile salmonids is considerable at the HOR study area. In addition to studying localized effects of predatory fish manipulation (see Section 8.2.3, "Conduct a Pilot Predatory Fish Relocation Study"), it is recommended that additional study be pursued into the potential effects of changing recreational fishing regulations for striped bass and other predatory fish species. The goal of such study would be to assess the prospects for an increase in the survival of juvenile salmonids, including those emigrating from the San Joaquin River region through the HOR study area.

The California Department of Fish and Game (now California Department of Fish and Wildlife) recently proposed changes to fishing regulations for striped bass (DFG 2011). The changes included generally increased bag limits and decreased size limits, with very large bag limits and no size limit in a "South Delta Hot Spot" region (including Clifton Court Forebay and portions of nearby channels such as Old River and West Canal). The California Fish and Game Commission (2012) rejected this proposal amid concerns from the recreational fishing community about potential adverse effects on the fishery which is currently in decline. In addition, leading fish biologists have expressed concerns about potential adverse effects on the Delta ecosystem, such as compensatory increases in predation by other predatory fishes and increases in the abundance of fishes that may compete with threatened fishes (Moyle and Bennett 2010). Therefore, it is recommended that additional studies be conducted into the potential effects of changes in fishing regulations. It is important to note that DWR cannot implement any changes to fishing regulations; these are the purview of the California Fish and Game Commission.

Under this recommendation, DWR would facilitate studies that would inform future decision making, with the recognition that a broader California Resources Agency effort probably would be needed to engage stakeholders from the recreational fishing and other communities (e.g., scientific and environmental organizations) in order to explore fully all considerations related to the feasibility and utility of changes in fishing regulations. Any studies undertaken as part of this recommendation should adhere to the guidelines of Grossman et al. (2013) for studies of predation in the Delta, and should include consideration of:

- changes in survival of listed species (e.g., juvenile Central Valley steelhead, including those from the San Joaquin River basin, and delta smelt) and other species of concern (e.g., juvenile San Joaquin River fall-run Chinook salmon);

- age-specific changes in abundance of striped bass; and
- changes in fishing opportunities (e.g., catch rates of recreational fishers).

8.3 BEHAVIOR AND DENSITY CHANGES IN PREDATORY FISHES

8.3.1 ASSESS PREDATORY FISH MOVEMENTS AS PART OF A PILOT PREDATORY FISH RELOCATION STUDY

It is recommended that predatory fish movements be studied as part of a pilot predatory fish relocation study (see Section 8.2.3, "Conduct a Pilot Predatory Fish Relocation Study"), if the study includes relocation of predators to other parts of the Delta. As described in Appendix J, "Recommended Aspects of a Pilot Predatory Fish Relocation Study," it may be desirable to hold captured predatory fishes in net pens during assessments of changes in survival of tagged salmonids in reaches that have had predatory fishes removed; after completion of the study, the captured predatory fishes could be released (Cavallo et al. 2013). In this case, an assessment of predatory fish movement would not be required. If, on the other hand, predatory fish are relocated elsewhere in the system, then it is recommended that their movements be tracked with acoustic tagging to assess the locations to which they disperse and determine whether they return to the HOR study area (or to other areas from which they were relocated).

Important considerations for such a study include the locations to which releases of predatory fish should be made, particularly because of the potential to enhance predation on listed fishes in other parts of the Delta. Bowen and Bark (2012) suggested that relocating predatory fish from the HOR study area could involve moving captured fish to San Luis Reservoir; however, this may not be desirable because it would remove predatory fish from the Delta system and therefore could provide less opportunity for recreational fishing. Additionally, relocating fish raises concerns about spread of disease between populations. As noted in Section K.2, "Predation Reduction," of Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan," the Bay Delta Conservation Plan proposes only localized reduction of predatory fishes to relieve predation pressure at hotspots, rather than achieving a system-wide reduction in predatory fishes.

8.3.2 ASSESS PREDATORY FISH DENSITY IN RELATION TO PREDATION HOTSPOTS

In association with a study of predation hotspots (see Section 8.2.4, "Study Effects of Physical Barriers on Location of Predation Hotspots"), it is recommended that predatory fish density be assessed by species and seasonally to determine whether there is evidence of a concentration of predatory fishes at predation hotspots compared to other areas where predation is not so intense. It is of interest to determine whether physical and environmental conditions as well as predatory fish density contribute to predation hotspots. For example, do hotspots have modest densities of predatory fishes that are not significantly different from densities in other areas, but these fishes are more efficient in feeding because of physical and/or environmental conditions? (Examples of such hotspots include areas of flow reversals at the intersection of riverine conditions with tidally influenced areas; see Section 8.2.4, "Study Effects of Physical Barriers on Location of Predation Hotspots.")

Predation hotspots are not solely attributable to predatory fishes; thus, the potential for predation by other piscivorous taxa (bullfrogs, birds, river otters, harbor seals, and sea lions) at hotspots is also recommended for investigation. Clark et al. (2009) and Miranda et al. (2010) examined the abundance of piscivorous birds at

Clifton Court Forebay and at the south Delta export facility's salvage release sites. Similar methods could be applied to evaluate the evidence of high densities of piscivorous birds relative to predation hotspots at the HOR study area and along the main migration routes through the south Delta. In addition, avian scat and river otter latrine sites could be sampled for Chinook salmon and steelhead otoliths/scales and scanned for acoustic tags.

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APPENDIX A

Additional Background on the Study Area and Nearby Areas

A.1 HISTORIC DELTA

The Sacramento–San Joaquin Delta (Delta) was considered a barrier by the first explorers of the region in the late 1700s. Crossing the myriad of sloughs, wetlands, and flooded lands discouraged exploration and development (Thompson 1957). Further exploration effort was suppressed by the hostile reception by native residents. From the late 1700s through the early 1840s, most exploration of the region centered around disrupting native presence, forming missions, and hunting for fur (Thompson 1957).

Modern development of the Delta began with the discovery of gold resources in 1848 (Lund et al. 2007; Thompson 1957). In the ensuing months, many coastal settlements were deserted as the masses migrated inland. Settlement was kept in check because of the limitations and challenges of sailing, the primary mode of transportation at that time in the area (Lund et al. 2007). However, steam-powered railroads became available after the 1850s, and the rate of settlement and development increased substantially (Thompson 1957). Many individuals soon discovered that agricultural opportunities surpassed those of mining, and the early 1850s marked the beginning of Delta wetland conversion and levee construction.

The federal Swamp Lands Act of 1850 was a major legislative enactment that intensified and facilitated reclamation of Delta lands (Lund et al. 2007; Thompson 1957). This law ceded federal swamplands to the states to encourage land reclamation, and California received nearly 202,343 hectares within the Delta (Lund et al. 2007). Creation of the Board of Reclamation in 1861 further facilitated reduction of floodplain and wetland habitat by creating reclamation districts from collectives of smaller parcel owners, the objectives of which were to enclose large areas defined by natural levees for agricultural development and to provide flood management (Lund et al. 2007). Ninety-three of these local entities still operate within the Delta today, with primary responsibility for providing levee maintenance (Lund et al. 2007).

Technological advances played a major role in reclamation. The first mechanized equipment for levee construction was developed in 1865 (Thompson 1957). Large-scale reclamation escalated as mechanized power was applied to levee construction, land clearing, ditch building, dredging, and pump-powered draining (Lund et al. 2007). The influence of these institutional and technological innovations on the reclamation of Delta lands is shown in Table A-1. Reclamation of the McCormack-Williamson Tract in 1934 marked the end of those activities that formed the primary physical features characterizing the present-day Delta.

Table A-1
Magnitude of Reclamation in the Sacramento–San Joaquin Delta, 1860–1930

Decade	Hectares Reclaimed	Cumulative Reclaimed Hectares
1860–1870	6,070	6,070
1870–1880	37,231	43,301
1880–1890	28,328	71,629
1890–1900	23,472	95,101
1900–1910	35,612	130,713
1910–1920	38,040	168,753
1920–1930	9,712	178,465

Source: Thompson 1957

A.2 SAN JOAQUIN RIVER

The San Joaquin River is the second longest river in California, measuring approximately 530 kilometers (km). The watershed originates high on the western slopes of the Sierra Nevada and drains most of the area from the southern border of Yosemite National Park south to Kings Canyon National Park.

The region's climate is characterized by long, hot summers and mild winters, with an approximate average annual precipitation of 15 centimeters (USACE 1993). Precipitation occurs primarily between November and April, and very little rainfall occurs during the summer months. Pulse flows occur in the basin from intense rainfall during the late fall and winter, and from snowmelt during the spring and early summer (USACE 2000). Higher peak-discharges occur from rainfall events, but the duration of these events typically is not as lengthy as those occurring from snowmelt (USACE 2000). Annual flow characteristics are affected substantially by water resources development that has occurred over the past approximately 130 years, including large multipurpose reservoirs, levee and channel improvements, bypasses, and local diversions (USACE 1993).

Surrounding land use is primarily agricultural, accounting for approximately 85% of the region's water use allocations (DWR 1994). The pattern of channel networks in the Delta is distributary (branches off from the main channel), with the division of the channel network into numerous individual channels producing a distinctive anastomosing channel network (Mount 1995). The distributary drainage pattern is characterized by high gradient tributaries discharging into low-gradient areas, delivering high sediment loads (Mount 1995). The major tributaries to the San Joaquin River, all of which are located upstream from the Head of Old River (HOR) at the divergence of the San Joaquin River and Old River (HOR study area), include the Stanislaus, Tuolumne, and the Merced rivers (Figure A-1). Currently, all salmonid production occurs in the San Joaquin River tributaries; the mainstem serves as a migratory corridor. Each of these rivers has been greatly affected by dredge mining, and the bulk of the finer sediments that made up the historical alluvial valley fill of these three tributaries has been transported downstream into the San Joaquin River (USACE 2000). This process continues to transport and deposit large quantities of fine sediments into the San Joaquin River (USACE 2000).

A.3 STANISLAUS RIVER

The Stanislaus River is approximately 154 km long, originates on the western slope of the Sierra Nevada, and flows southwest to the confluence with the San Joaquin River on the floor of the Central Valley. Several reservoirs and dams control flows in the Stanislaus River for flood management, power generation, and water supply. Water uses include irrigation and municipal needs, recreational activities, and water quality control. Goodwin Dam is approximately 94 km upstream from the San Joaquin-Sacramento River confluence and blocks the upstream migration of anadromous fish (S. P. Cramer and Associates 2001).

The Stanislaus River is designated critical habitat for California Central Valley steelhead distinct population segment (DPS). The California Central Valley steelhead is present in small numbers in the Stanislaus River, and smolts have been captured in rotary screw traps at Caswell State Park and Oakdale annually since 1995. The California Central Valley spring-run Chinook salmon evolutionarily significant unit (ESU) has been extirpated from the Stanislaus River, primarily due to dam construction causing elimination of spawning habitat. California Central Valley fall-run Chinook salmon ESU is present in the Stanislaus River, although populations are depressed below historical levels (FISHBIO Environmental 2007; NMFS 2011).

A.4 TUOLUMNE RIVER

The Tuolumne River is approximately 240 km long, originates on the western slope of the central Sierra Nevada, and flows west to the confluence with the San Joaquin River on the floor of the Central Valley. La Grange Dam, completed in 1883, is located approximately 84 km upstream from the San Joaquin River confluence, and constitutes a the migration barrier to anadromous fishes (Turlock Irrigation District and Modesto Irrigation District 2010).

The Tuolumne River is designated critical habitat for California Central Valley steelhead DPS, and populations are currently present (Ford and Kirihara 2010; NMFS 2011). The California Central Valley spring-run Chinook salmon ESU has been extirpated from the Tuolumne River (NMFS 2011) due to dam construction causing elimination of spawning habitat. The California Central Valley fall-run Chinook salmon ESU is present in the Tuolumne River. Population estimates have shown a decline through the last decade (Turlock Irrigation District and Modesto Irrigation District 2010).

A.5 MERCED RIVER

The Merced River is approximately 233 km long, originates on the western slope of the central Sierra Nevada, and flows west to the confluence with the San Joaquin River on the floor of the Central Valley. The Crocker-Huffman Dam, completed in 1910, is located approximately 84 km upstream from the San Joaquin River confluence and constitutes a the migration barrier to anadromous fishes (USFWS 2007).

An annual steelhead run in the Merced River has not been documented (USFWS 2007). However, the National Marine Fisheries Service (NMFS) states that incidental catches of juvenile steelhead during monitoring efforts have occurred on the Merced River (NMFS 2007), and that the species' presence in the Merced River is assumed because of proximity, similar habitats, and historical presence when compared to the Stanislaus and Tuolumne rivers (NMFS 2011). The California Central Valley spring-run Chinook salmon ESU has been extirpated from the Merced River (NMFS 2011) due to dam building causing elimination of spawning habitat. A California Central Valley fall-run Chinook salmon ESU is present in the Merced River, although population estimates have been very low for many years (California HSRG 2012). The Merced River Fish Hatchery, located just downstream from Crocker-Huffman Dam, historically has supplemented naturally produced Chinook salmon populations.

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APPENDIX B

Focal Fish Species Information

B.1 FOCAL SALMONID SPECIES FOR PROTECTION AT HEAD OF OLD RIVER

B.1.1 CHINOOK SALMON—LIFE HISTORY AND JUVENILE SWIMMING CAPACITY

This appendix provides a synopsis of what is known about the life history and behavior of Chinook salmon (*Oncorhynchus tshawytscha*) with emphasis on the Sacramento–San Joaquin Delta (Delta).

Chinook salmon is in long-term decline in California, although the species is not in immediate danger of extinction. The Sacramento River has spring, fall, late-fall, and winter-runs of Chinook salmon (Kjelson et al. 1982; Williams 2006). By contrast, the San Joaquin River has supported only three runs: fall, late-fall, and spring with the latter two runs extirpated in the 1940s (Fisher 1994). At present, only fall-run Chinook salmon inhabit the San Joaquin River. Fall-run fish have been the most studied (Kjelson et al. 1982).

This section discusses the various life stages of salmonids. The terminology follows that of Allan and Ritter (1977). In chronological order, these terms are "egg," "alevin," "fry," "parr," "smolt," "adult," and "kelt." One additional term is used because authors in Central Valley studies use it with some frequency: "pre-smolt," defined as an anadromous salmonid undergoing the smoltification process that exhibits some characteristics of smolts but has not completed all the physiological, morphological, and behavioral changes of smolts. The term "juveniles" refers to the sexually immature stages of pre-smolts and smolts.

Chinook salmon are semelparous and show a wide array of life-history pattern adaptations that have allowed it to take advantage of diverse and highly variable lotic environments. Within two basic types of life-history strategies, stream-type and ocean-type, the variations are recognized as runs. Stream-type Chinook salmon juveniles overwinter in freshwater before entering the ocean, and spend usually more than 1 year in freshwater. Ocean-type adults become sexually mature while during the ocean phase and spawn soon after entering freshwater, in late summer and fall. Juveniles migrate to the ocean early in their first year of life. Both types are present in California (Moyle 2002), but San Joaquin River fall-run Chinook salmon exhibit an ocean-type life history (SJRRP 2008).

ADULT AND SPAWNING MIGRATION

Adult Chinook salmon are the largest of any Pacific salmon, typically measuring 75 to 80 centimeters (cm) in standard length and weighing 9 to 10 kilograms (kg). Adults can grow to 140 cm long and weigh up to 45 kg (Healey 1991; Moyle 2002). Males vary more in size than females at maturity, and for most populations, average males are smaller than average females (Quinn 2005). Growth is variable but often rapid in the ocean; thus, ocean-type Chinook adults are often larger than stream-type individuals.

To spawn, Chinook salmon leave the Pacific Ocean and return to their natal rivers over great distances. Upstream migration takes place mainly during the day, with fish apparently tracking stream odors on which they imprinted as juveniles (Healey 1991). Although most fish home to their natal stream, some stray and spawn in a different streams. Straying presumably is an adaptive mechanism that allows salmon to (re)colonize newly opened areas and mix genetically with other runs, especially those in streams close to their natal streams (Moyle 2002). During spawning migration, adult Chinook salmon mistakenly enter intake structures or unscreened diversions (Yoshiyama et al. 1998). Upstream-migrating adults may pass through the San Joaquin River or Old River, moving upstream through the Head of Old River (HOR) study area. The adult migration of Chinook salmon is

heavily concentrated from August through November, reflecting the numerical dominance of the fall-run salmon in the Sacramento-San Joaquin rivers (Williams 2006).

Despite the large variation in run timing in most rivers, spawning times tend to be similar among runs. Once the natal streams are reached, salmon select areas for holding, although fall-run Chinook salmon may spawn without any delay. Chinook salmon use a variety of freshwater habitats, but they more commonly spawn in larger mainstem rivers than other salmonids. Female salmon excavate redds in gravel deposits. When each redd is dug, the female essentially cleans an area measuring 2 to 10 square meters (m^2), loosening gravel and mobilizing fine sediments (particles less than 2 millimeters [mm] in diameter), so that the future embryos will have access to a steady flow of oxygen-containing water (Healey 1991). Females deposit eggs and males fertilize the eggs, and both cover the eggs with substrate immediately after fertilization. Chinook salmon have been observed digging redds and spawning at a variety of depths from a few centimeters to several meters (m), and at water velocities of 15 to 190 centimeters per second (cm/s), but most seem to spawn at depths between 25 and 100 cm and velocities of 30 to 80 cm/s (Healey 1991). Regardless of depth, the key to successful spawning is having an adequate flow of water around developing embryos, which means they have to be buried in coarse substrate with low silt content.

EGG

Generally, female Chinook salmon produce 2,000 to 17,000 eggs in their one-time only spawning event. Although the number of eggs increases with body size, this relationship is not as strong in Chinook as in other salmonids and varies among populations and runs (Moyle 2002). Survival of eggs in the Central Valley is highly variable between runs and years, but overall is considered generally low (Williams 2006). For maximum embryo survival, water temperatures must be between 5 and 13 degrees Celsius (°C), and oxygen levels must be close to saturation (Healey 1991; Moyle 2002). Under such conditions, embryos hatch in 40 to 60 days and remain in gravel as alevins for another 4 to 6 weeks until the yolk sac is fully absorbed when they emerge as fry.

ALEVIN AND PARR

Size at hatching and emergence depends on water temperature, with optimal water temperatures ranging between 5° and 8°C (Williams 2006). Fry generally are 30 to 40 mm long (Williams 2006).

After emerging from gravel, fry typically are washed downstream into back or edge-water areas, where velocities are slower than the channel thalweg, cover is dense, and prey items are abundant. Many disperse downstream, especially if high-flow events correspond with emergence (Healey 1991; Moyle 2002). Dispersal behavior shows variations among fry that emerge from a single redd, with larger individuals most likely to disperse (Bradford and Taylor 1997). Movement occurs mostly at night; for stream-type individuals, this movement tends to cease after a couple of weeks, when fry settle down into rearing habitat in streams or estuaries. Because ocean-type Chinook salmon juveniles may begin movement immediately, they may move through the Sacramento-San Joaquin Delta (Delta) and pass by the HOR study area. Therefore, it is important to understand the effect of any barrier installed at the HOR study area on the Chinook salmon juvenile life stage.

A major limiting factor for juvenile Chinook salmon is water temperature, which strongly affects growth and survival. For Central Valley fall-run Chinook fry, optimal water temperatures for growth and survival are 13° to 18°C (Marine 1997), although throughout the range of Chinook salmon, positive growth is experienced at water

temperatures of 5° to 19°C (McCullough 1999). At 22° to 23°C, mortality is experienced in wild populations, and very few individuals can survive water temperatures greater than 24°C for even short periods of time (Moyle 2002). At sub-lethal water temperatures, growth is reduced and predation rates increased as a consequence. Water temperature in the Delta in June is inversely proportional to survival of Chinook salmon juveniles as they pass through and out of the Delta (Baker et al. 1995; Kjelson et al. 1982).

Optimal juvenile rearing habitat contains instream structure (e.g., undercut banks, large woody debris) and canopy cover, an adequate food supply (aquatic and terrestrial invertebrates), suitable water velocities and depth, and low turbidity (SWRI 2003). In general, microhabitat use by juvenile Chinook salmon occurs in deeper and faster water as they grow larger. Microhabitat use and foraging behavior can be influenced, however, by the presence of predators (i.e., other fish, bullfrogs, piscivorous birds, river otters, harbor seals, and sea lions), which may force Chinook salmon to select areas of heavy cover and suppress foraging in more open areas. During the night, juvenile Chinook salmon may abandon their foraging areas in swift-moving water and retreat to quiet edge-waters or pools (Moyle 2002) as an energy-conserving measure or as a way to avoid nocturnal predators (e.g., Sacramento pikeminnow [*Ptychocheilus grandis*] in the Central Valley) (Moyle 2002).

While in freshwater, juvenile Chinook salmon are opportunistic drift feeders and eat a wide variety of terrestrial and aquatic insects. Juveniles feed mostly during the day, with peaks at dawn and during the afternoon. In the Delta, terrestrial insects are the most important food, but crustaceans also are eaten (Moyle 2002).

SMOLTIFICATION AND SEAWARD MIGRATION

Juvenile salmonids undergo a set of physiological and behavioral changes before they migrate to the sea. These changes are associated with their downstream migration and the transition from freshwater to marine habitats, and with the transformation from parr into smolts, a physiological process known as smoltification (Williams 2006). Smoltification typically occurs in the spring; if the fish do not migrate, most of these changes reverse and they remain parr, but often they smolt again the next spring (Williams 2006).

In general, stream-type juveniles move downstream and out to sea as smolts, at lengths of 80 to 150 mm fork length (FL), but wild ocean-type (fall-run) juveniles move downstream at smaller sizes (30 to 50 mm FL) to rear in the San Francisco Bay estuary. Movement into the estuary varies with year (Moyle 2002). Migrating juvenile salmon are susceptible to mortality from unscreened water diversions (Yoshiyama et al. 1998).

Hatchery contributions of juveniles and smolts, and their sizes, for this study were described in Chapter 5, "Methods." The swimming capacity of the hatchery Chinook salmon juveniles in this study was evaluated through a literature review of critical swimming speed (U-crit), a measure of maximum sustained swimming capacity, and sustained swimming speed (Brett 1964; Peake 2008). The lowest U-crit value reported in the literature for Chinook salmon juveniles from Central Valley stock origin is 4.37 body lengths per second (BL/s) at a water temperature of 12°C (Katzman 2001; Swanson et al. 2004) (Table B-1). The HOR study area experienced temperatures greater than 12°C for all 3 years of data collection while a barrier was in place (Figures 3-21, 3-22, 3-23, and 3-24 in Chapter 3, "Physical Parameters"). Presumably, the sustained swimming speed for the hatchery Chinook juveniles in this study due to warmer water is greater than or equal to 4.37 body lengths per second (BL/s) when the barriers are in place. Swanson et al. (2004) used a 120-minute time interval; thus, it was assumed that the hatchery fish in this study could swim 4.37 BL/s for up to, but not more than, 120 minutes.

Table B-1
Swimming-Speed Capacity of Juvenile Chinook Salmon from Central Valley Stock Origin

Chinook Salmon Size	Water Temperature (°C)	Source	Swimming Metric	Swimming Speed (body lengths per second)	Swimming Speed Time Interval (minutes)
87–96 mm SL[1]	17	Wild	U-crit	5.91 to 6.26	20
62–79 mm SL[2]	12	Hatchery	Sustained	4.37 to 5.56	120
56–77 mm SL[2]	19	Hatchery	Sustained	4.91 to 6.75	120

Notes: mm = millimeters; SL = standard length; U-crit = critical swimming speed; °C = degrees Celsius

[1] For Katzman (2001), swimming speed reported is the range.

[2] For Swanson et al. (2004), the swimming speed is the mean, in body lengths per second, for the reported size range.

Sources: Katzman 2001; Swanson et al. 2004

As the juveniles and/or smolts move downstream in the San Joaquin River from their natal streams they pass the HOR study area at the divergence of the San Joaquin and Old rivers. Some smolts remain in the San Joaquin River and pass through the Delta, primarily through the eastern and central Delta, on their way to the Pacific Ocean. This route is >89.0 kilometers (km) from the HOR study area to Chipps Island via Stockton (Google Earth 2013).

Another possible route is for the juveniles and/or smolts to enter Old River and migrate through the southern Delta, passing by the entrance of the Tracy Fish Collection Facility (TFCF); this route is >86.2 kilometers (km) from the HOR study area to Chipps Island via the TFCF entrance (Google Earth 2013). In addition, some juveniles that pass the HOR study area and entered Old River could enter the Central Valley Project (CVP) or State Water Project (SWP) pumping plant intakes, subject to salvage, and transported by truck downstream to be released in the western Delta.

PACIFIC OCEAN

Once reaching the Pacific Ocean, juvenile Chinook salmon from California rivers tend to stay along the California coast, although a general northward movement of fish may occur, causing a few to be found off Washington state. Concentration of California salmon in nearby marine waters is not surprising, considering their high productivity. This productivity is caused by upwelling that is generated by the California Current, a southward-moving current originating in the Gulf of Alaska. In these food-rich waters, juvenile Chinook salmon swim at depths that vary with the season (0 to 100 m), but they typically swim deeper than most other salmon. Ocean survival of salmon declines during years when the California Current does not flow as strongly and upwelling decreases (Moyle 2002). Chinook salmon spend a few months to seven years at sea (Williams 2006).

B.1.2 CHINOOK SALMON—FALL-RUN

STATUS

The Central Valley fall-run evolutionarily significant unit (ESU) covers fall-run and late fall-run salmon in the Sacramento and San Joaquin rivers and tributaries (Lindley et al. 2004; Moyle 2002). This ESU always has been the most abundant run in the Sacramento River watershed, historically numbering over 1 million spawners in

some years (Yoshiyama et al. 1998). Although California Central Valley fall-run Chinook salmon is not listed as threatened or endangered under the federal Endangered Species Act (ESA), it was classified in 2004 as a Species of Concern by the National Marine Fisheries Service (NMFS). These are the most common Chinook salmon in the southern Central Valley and make up most of the juvenile Chinook salmon that pass the HOR study area each year.

ADULT AND SPAWNING MIGRATION

Fall-run Chinook salmon are ocean-type Chinook salmon, adapted for spawning in lowland reaches of large rivers and their tributaries.

Fall-run Chinook salmon adults enter Central Valley rivers to spawn between late summer and fall (Williams 2006). Historical spawning habitat of the fall-run Chinook salmon remains available below existing dams. These fish spawn shortly after entering their natal river. The strategy allows fall-run salmon to take advantage of extensive high-quality spawning and rearing areas in valley reaches of rivers that are often too warm to support salmon in summer. Because of the timing of the fall-run, adults pass by the HOR study area before the spring barriers are placed.

Most fall-run Chinook spawn in gravel and cobble areas, primarily at the head of riffles of the main rivers and tributaries in the Central Valley and foothills. Gravel and cobble sizes can range from 0.2 to 15 cm (SWRI 2003). Preferred water velocity for spawning is 0.4 to 1.2 m/s. Spawning typically begins when the water temperature cools to approximately 14° or 15°C, lasting from late September to December, peaking in late October (Fisher 1994; Williams 2006).

EGG

Sacramento fall-run Chinook salmon appear to have exceptionally high fecundity for their size (Healey 1991). The average fecundity of females in the Sacramento River has been estimated to be about 5,500 eggs (Fisher 1994).

ALEVIN, PARR, AND JUVENILE

Fall-run fry emerge from December into April, depending on the date of spawning and water temperature during incubation. They exhibit two main patterns within their ocean-type life-history strategy. Most begin migrating as fry, shortly after emergence (Hatton 1940), and most of these apparently rear for 1 to 3 months in the Delta before moving into the bays. However, some continue directly through Carquinez Strait into San Pablo Bay (Hatton 1940). Analogous groups in Puget Sound, Washington, have been described as “delta users” and “fry migrants” (Greene and Beechie 2004). Of the Chinook salmon that do not leave the spawning reaches as fry, most do so as juveniles by May or early June, before the lower river water temperature become lethal or near lethal, and they pass fairly quickly through the Delta. These larger migrants are sometimes called “fingerlings” or “90-day Chinook,” and are undergoing smoltification. The relative contributions of fry and juveniles migrants to adult escapement are not known, but Williams (2006) has suggested that fry do not survive as well as juvenile migrants.

SMOLT AND SEAWARD MIGRATION

Downstream migration of fall-run Chinook smolts occurs from March through July (Fisher 1994). Reservoirs increase overwinter water temperatures of rivers than was the case historically, so that embryos and alevins develop more rapidly since the development of dams. Monitoring (Snider and Titus 2000a, 2000b, 2000c) indicates that Chinook fall-run fry migrants in the Sacramento River downstream of Shasta Dam begin their migration approximately 1 month earlier than indicated by pre-dam installation monitoring, as reported by Rutter (1904) and Hatton and Clark (1942). The consequences of the change in timing are unknown, but it could be significant (Williams 2006). It should be noted that historic juvenile migration timing should not be directly compared to current juvenile migration timing without considering the genetic influences from hatchery stock and climate change.

The peak exit period for juveniles and smolts out of the Delta and into the estuary is from April through June (Kjelson et al. 1982). Presumably, a peak exists in emigration to the ocean by Chinook salmon, as they pass by the HOR study area during that same period (Table B-2). Kjelson et al. (1982) have suggested that the migration is driven by water temperature. For this reason, it is speculated that the exit of smolts from the San Joaquin River may be earlier than the exit from the Sacramento River because of the more southerly position of the San Joaquin River in the Central Valley.

Table B-2
Dates of Chinook Salmon Salvages from January 1 through June 30
for 10 Years of Data Collected at the Skinner Delta Fish Protective Facility (Byron, California)

Year	First Salvage	Beginning Peak	End Peak	Last Salvage
2003	January 1	January 13	April 24	June 27
2004	January 1	January 14	May 11	June 17
2005	January 1	January 28	June 9	July 3
2006	January 1	February 21	June 22	July 5
2007	January 5	February 23	May 3	June 12
2008	January 13	January 31	May 29	June 7
2009	February 4	April 19	May 16	June 11
2010	January 23	January 26	June 2	July 6
2011	January 1	February 18	June 22	July 21
2012	January 5	–	–	–

Source: Compiled by Turnpenny Horsfield Associates and AECOM from data from CDFG 2012

PACIFIC OCEAN

Once reaching the Pacific Ocean, juveniles switch to a fish diet, and growth is rapid. At age 2, Sacramento River fall-run Chinook salmon average approximately 55 cm FL; at age 3, approximately 70 cm FL; at age 4, approximately 90 cm FL; and at age 5, approximately 100 cm FL (Moyle 2002). Considerable variation exists in length at different ages. Fall-run Chinook salmon spend 1 to 4 years at sea, although fall-run from the San Joaquin River spend the least amount of time, and late fall-run Chinook spend the most time (Myers et al. 1998). Fall-run

Chinook salmon spend most of their oceanic life nearshore. It is speculated that the juveniles and young adults remain close to their natal river.

B.1.3 CHINOOK SALMON—SPRING-RUN

STATUS

The Central Valley spring-run Chinook salmon ESU has been reduced from an estimated 17 historical populations to only four extant populations with consistent spawning runs: Mill, Deer, and Butte creeks, and the Feather River (DWR 2003; NMFS 2008). The reintroduction of an experimental population of spring-run Chinook salmon began in 2014, and any barrier at the HOR study area needs to consider the potential impacts on the reintroduction of these fish.

Historically, spring-run Chinook salmon were likely the most abundant species in the San Joaquin River watershed (Williams 2006; Yoshiyama et al. 1998). However, they have undergone the most dramatic decline among the four Chinook salmon runs in the Central Valley, mainly as a result of intensive in-river harvest pressure and massive losses (70% to 90%) of spawning and rearing habitat in the upper watersheds from construction of hydropower and irrigation diversion projects (NMFS 2008; Yoshiyama et al. 1998).

In the mainstems of the Sacramento and the Feather rivers, spring-run Chinook salmon have undergone significant hybridization with fall-run. Because of the small number of non-hybridized populations remaining and low population sizes, the Central Valley spring-run Chinook ESU was listed as threatened by the State of California in 1998 and by NMFS in 1999 (64 FR 50393, September 16, 1999; Title 50, Part 223 of the Code of Federal Regulations [50 CFR 223]). Critical habitat was designated in 2005 by NMFS (70 FR 52488, September 2, 2005; 50 CFR 226).

ADULT AND SPAWNING MIGRATION

Adult spring-run Chinook salmon enter freshwater in the spring, over-summer in pools while their gametes mature, and spawn in late August to early October (Fisher 1994). Adults pass upstream into their holding areas from February into early July, with migration peaking in mid-April in Butte Creek, mid- to late May in Mill and Deer creeks, and May and June on the Feather River (Williams 2006). If the restored spring-run Chinook salmon run in the San Joaquin River is similar to those in the Sacramento River tributaries, then the adults would pass any barrier in place at the HOR study area.

In rivers, adult spring-run Chinook salmon select large, deep (usually greater than 2 m) pools before spawning. These pools typically have bedrock bottoms and moderate velocities. In California, spring-run Chinook salmon usually hold where mean water column velocities are 0.15 to 0.8 m/s, often under ledges, in deep pockets, or under the "bubble curtain" formed by water plunging into pools (Moyle et al. 1995). The fish do not necessarily stay in the same pool all summer long, but move between pools, usually with a net upstream movement. Holding areas often are near spawning areas. Spawning areas may occur at the tailouts of holding pools.

Spring-run Chinook salmon spawn in late August through early October, with peak spawning in mid-September (Fisher 1994). During the spawning period, water temperatures are decreasing. The species' spawning areas are in the upper reaches of the Sacramento River mainstem and its principal tributaries (Healey 1991).

Typically, spring-run Chinook salmon spawn farther upstream and at higher elevations than fall-run. In these areas, water cools to suitable temperatures earlier than in the fall-run spawning areas.

Historically, spatiotemporal segregation helped to maintain reproductive isolation on the McCloud River (DFG 1998) and Sacramento River below Shasta Dam (Moffett 1949). However, Slater (1963) reported that the spawning periods of the two runs overlapped, resulting in hybridization. Hybridization between spring- and fall-run Chinook also has occurred in the Feather River (Lindley et al. 2004).

EGG

The average fecundity of females in the Sacramento River has been estimated to be approximately 4,900 eggs (Fisher 1994). Spring-run Chinook salmon spawn when water temperatures are decreasing; evidence exists that their eggs are more tolerant of warm water shortly after fertilization than they are later.

ALEVIN, PARR, AND JUVENILES

The juvenile emergence period occurs from November through March for spring-run Chinook salmon (Fisher 1994). Juveniles may rear in the Delta for 3 to 15 months, depending on flow conditions (Fisher 1994). Spring-run Chinook salmon require cool water while they grow in freshwater over the summer. Since most cool-water habitat is now located upstream of impassable dams, water temperature is a limiting factor to the spring-run.

SMOLT AND SEAWARD MIGRATION

Spring-run Chinook salmon in the Sacramento River exhibit an ocean-type life history, emigrating as fry, sub-yearlings, and yearlings. Most spring-run emigrate from December through March, primarily as newly emerged fry, especially in Butte Creek, but some migrate as larger parr from March through June. Fall-run Chinook salmon produced by the hatcheries are regarded as surrogates for these larger spring-run parr migrants. In the future, after spring-run Chinook salmon are restored to the San Joaquin River, spring-run juveniles and smolts are likely to encounter any barrier type installed at the HOR study area if it is in place from April through June.

Another group of spring-run Chinook salmon parr and juveniles hold over through the summer and migrate in the fall or winter. Only a few hold over until the following spring and migrate as 1-year-old or older juveniles (Williams 2006).

PACIFIC OCEAN

Spring-run Chinook salmon have a wider ocean distribution than fall-run, often leaving nearshore waters in their first year of life and seeking more northerly high-sea areas (Healey 1991). Recent observations show that while the vast majority of spring-run Chinook salmon leave Butte Creek as young-of-the-year, yearling outmigrants account for approximately 25% of the ocean catch of Butte Creek spring-run Chinook (Ward et al. 2002).

B.1.4 STEELHEAD

The iteroparous steelhead trout (*Oncorhynchus mykiss gairdneri*) (Page et al. 2013) includes stream-resident rainbow trout and anadromous steelhead (Moyle 2002) in the Sacramento and San Joaquin rivers below all impassable dams. In this report, *O. mykiss* is used to refer to rainbow trout and steelhead collectively. Resident

rainbow trout can have offspring that are anadromous. This rare characteristic is strongly related to parental genetic composition (Stillwater Sciences 2006). Also, anadromous *O. mykiss* can become residents under optimal rearing conditions in freshwater (Cramer and Beamesderfer 2006). For example, streams with water temperatures consistently averaging 11° to 15°C during summer and rarely exceeding 18°C would provide *O. mykiss* with suitable habitat to complete all life stages. A resident strategy would be one possible outcome.

Historically, the greatest steelhead production in the Central Valley came from Sacramento River populations (Lindley et al. 2006). Most observations reported herein derive from this population because no studies of San Joaquin steelhead were completed until 2001 (McEwan 2001).

Historically, steelhead were widely distributed throughout the Sacramento and San Joaquin River watersheds, and were composed of summer- and winter-runs. Presently, only the winter-run persists in the Sacramento–San Joaquin River system (Williams 2006). Because of the construction of dams, summer steelhead were prevented from reaching tributaries in the upper reaches of the watersheds where they previously over-summered in deep, cool pools. As a consequence, summer steelhead in the Central Valley are now extirpated (McEwan 2001).

STATUS AND HISTORICAL DISTRIBUTION

The California Central Valley steelhead distinct population segment (DPS)[1] was listed as threatened in 1998 (63 Federal Register [FR] 13347–13371) under the federal ESA. The listing of Central Valley steelhead trout DPS was affirmed in 2006 (50 FR 834–862) (Good et al. 2005). The term "evolutionarily significant unit (ESU)" also is found in literature. In this case, ESU and DPS are equivalent terms, meaning "species" under the ESA (71 FR 834–862). The Central Valley steelhead trout DPS (Figure B-1) includes all naturally spawned populations of steelhead in the Sacramento and San Joaquin rivers and their tributaries below major dams. The populations in the two artificial propagation programs at the Coleman National Fish and Feather River Steelhead hatcheries, are also part of the DPS, but steelhead from the two other hatchery programs (Nimbus Fish Hatchery on the American River and the Mokelumne River Fish Hatchery) are not.

An estimated 95% of the historically available spawning habitat is inaccessible to steelhead because of dam construction and water projects (McEwan 2001; Lindley et al. 2006). The lost habitat resulted in a significant decrease in the population from an estimated 1 to 2 million adult steelhead in the Sacramento–San Joaquin River watershed to as little as 40,000 individuals in the 1960s, and to less than 10,000 in the early 1990s (McEwan 2001).

Some factors contributing to the decline of Central Valley steelhead include habitat alteration, such as bank protection (rip-rap and armoring), dredging, and gravel mining. Some biological stressors also have been identified as contributing to the decline of steelhead: predation, invasive species, and disease (McEwan 2001). However, the two most important factors in the decline of steelhead are the development of water export related resources and management of that water in the Central Valley (McEwan and Jackson 1996). Furthermore, NMFS (1997) has suggested that the decline in the steelhead population has curtailed the species' resiliency to natural factors such as predation, drought, and poor ocean conditions. Lindley et al. (2006) concluded that insufficient information existed to adequately assess the risk of population extinction for Central Valley winter run steelhead.

[1] West Coast steelhead (*O. mykiss*) includes 10 DPS (NOAA 2006). DPS policy is found at 61 FR 4722, February 7, 1996.



Source: 71 *Federal Register* 834–862

Figure B-1 **California Central Valley Steelhead Range**

ADULT

After spending 1 to 4 years at sea, adult Central Valley steelhead return to the Sacramento River weighing between 1.4 and 5.4 kg (Moyle 2002) and measure 35 to 65 cm TL. Steelhead rely on olfactory cues to find their natal stream during the spawning migration. Most steelhead make their way into freshwater beginning in August, with a peak in September and October (McEwan 2001). However, in nearly every month of the year, steelhead migrate up the Sacramento River (Moyle 2002). A barrier in place at the HOR study area may influence the behavior of adults or change the passage difficulty of migrating upstream. During the upstream spawning migration, many adults travel through the area of the HOR study area. Changes in flow patterns by the construction of any barriers may have impacts on upstream migrating adults. No such effects have been quantified to date.

Williams (2006) and McEwan (2001) have suggested that some Central Valley steelhead may hold for months in spawning streams while gamete maturation is completed, but now this life history pattern is rare because of the loss of suitable habitat. Thus, most steelhead become sexually mature in the ocean and spawn soon after reaching their spawning sites (Williams 2006). Spawning in the upper Sacramento River generally occurs between November and late April with a peak from early January through late March (Reclamation 2004). The spawning peak occurs when water temperatures throughout much of the Sacramento River are suitable to support egg incubation and emergence. It is suspected that these conditions would be similar in the San Joaquin River.

In the Sacramento River watershed, steelhead spawn in Butte, Deer, and Mill creeks; the American, Feather, Stanislaus, and Yuba rivers; and the Sacramento River below Keswick Dam (Figure B-1) (CALFED 2010; Moyle 2002). Under historical conditions, steelhead spawned in much higher gradient reaches in the Sacramento River and its tributaries than any other steelhead DPS in western North America (McEwan 2001).

Spawning occurs where well-oxygenated water exists, good hyporheic flow is found, and water temperatures are appropriate (McEwan and Jackson 1996). The female digs a redd in a riffle, successively digging, spawning, and resting as she moves upstream. Water velocity varies between 0.2 and 1.5 m/s, and depth varies from 0.1 to 1.5 m. Typically, one dominant male will spawn with one female, but other males also can participate (Moyle 2002). Larger steelhead spawn in the higher range of water velocity (McEwan 2001). Steelhead redds generally are found in substrates ranging from 0.6 to 10 cm in diameter (Bjornn and Reiser 1991).

Steelhead is iteroparous: surviving post spawners can return to the ocean. After a year or more, gamete rematuration occurs and steelhead migrate back to their natal streamto spawn again. Although some kelts (post-spawned adults) have been documented in the Sacramento River, probably few repeat spawners exist in this population (Reclamation 2004). Repeat spawners are observed returning every other year (Moyle 2002). Photoperiod, stream flow, and water temperature appear to influence emigration timing (Holubetz and Leth 1997).

Adult post-spawning outmigration occurs from March through July. The steelhead kelts moving from the southern Central Valley tributaries from April to June will travel through the HOR study area while a barrier is in place.

EGGS

Female steelhead lay approximately 2,000 eggs per kg of body weight and leave the spawning ground soon after laying their eggs, while males remain to have a chance to spawn with more than one female (Moyle 2002). Egg hatching is temperature-dependent, but generally requires 4 weeks.

No Central Valley–specific information exists about water temperature requirements for successful spawning and incubation, but values derived from other steelhead stocks in more northerly locations suggest that optimal spawning water temperatures are between 4° and 11°C, with egg mortality occurring at water temperatures above 13°C (Bell 1986; Bovee 1978; Hooper 1973; McEwan and Jackson 1996; Reiser and Bjornn 1979).

FRY

After hatching, sac-fry will remain in the gravel 4 to 6 weeks before emerging (McEwan and Jackson 1996; Shapovalov and Taft 1954). Once the yolk sac is fully digested, fry emerge from the gravel and become free-swimming (Quinn 2005). The timing of emergence by fry (less than or equal to 50 mm total length [TL]) is strongly influenced by water temperature (Shapovalov and Taft 1954). Fry congregate along the bank in shallow water (Barnhart 1986), where velocity is low. During spring rearing, fry may be vulnerable to entrainment at unscreened diversions.

JUVENILE: PARR AND SMOLT

In rivers, juvenile steelhead search for energetically advantageous positions (Bowen 1996). They tend to select velocity shelters adjacent to swift velocities that provide abundant drifting invertebrates. These shelters allow maximize energy intake while minimizing the cost of swimming to maintain position (Everest and Chapman 1972; Fausch 1984). Steelhead may remain in these velocity shelters for a long time if the position is of sufficient quality, affording low focal velocity and high-velocity shear. These energetically advantageous positions can increase growth and survival, and individual fish may display aggressive behavior to defend them (Bowen 1996). In more open habitat (e.g., large pools), juveniles are not as territorial and are more prone to school with similar-size congeners (Moyle 2002). While in the river, they feed primarily on drifting invertebrates (Moyle 2002).

The preferred water temperature range for juveniles is between 7 and 14°C (Bell 1986). At water temperatures greater than 21°C, steelhead have trouble extracting oxygen from the water (Hooper 1973). The upper, lethal thermal limit is between 23.9°C (Bell 1986) and 24.0°C (Nielsen et al. 1994).

The triggers that influence whether or not juvenile *O. mykiss* migrate to the sea are complex (Quinn 2005). *O. mykiss* may become resident and spend their entire life in freshwater. Thus, *O. mykiss* released at Durham Ferry could conceivably swim upstream and survive to reproduce. However, for those individuals that choose anadromy, they spend 1 to 3 years in freshwater before outmigrating; a tiny proportion in California, perhaps 0.3%, emigrate when older than 4 years (Quinn 2005). Hatcheries in the Central Valley produce *O. mykiss* that emigrate to the ocean when older than 1 year.

The Mokelumne River Fish Hatchery in Clements, California, provided the juvenile steelhead used to evaluate fish barriers in this report (Table 5-1 in Chapter 5, “Methods”). Brood stock for steelhead are collected and spawned in November and December (Smith, pers. comm., 2013). The hatchery maintains the juveniles for more than 1 year to mimic the winter-run steelhead life history.

The Mokelumne River Fish Hatchery uses the following four process stages of development (Smith, pers. comm., 2013):

(1) Eggs are incubated at 11.1 to 12.2°C until they hatch.

(2) Once the sac-fry fully absorb their yolk sacs, the fry are fed at a high rate with a target of an 18% to 20% weight increase per week.

(3) The parr then are moved to outdoor "raceway ponds" at 60 to 80 mm TL, and are fed 2% of their total body weight per day.

(4) In the autumn, the juveniles are starved on alternating weeks to keep the growth rate slow and meet the stocking target of 180 mm TL in February, when the fish are approximately 15 months old.

The parr may undergo the behavioral and physiological changes of smoltification. For this study, the fish were held past the stocking target and used in the period of experimental releases from April through June.The juveniles were parr or smolts, depending on the degree of smoltification of each individual, and ranged in size from 110 to 320 mm TL (Table 5-1 in Chapter 5, "Methods"). The juveniles produced in the hatchery were used in this research as surrogates for naturally produced (wild) steelhead, and surgically implanted with acoustic transmitters and released in the San Joaquin River 24.4 km upstream of the HOR study area (see Chapter 5, "Methods").

The U-crit (Brett 1964; Peake 2008) was evaluated via literature review. The reported U-crit for hatchery steelhead ranged from 3.02 to 5.76 BL/s (Table B-3). Steelhead on the small end of the size range of the species was used in the experimental releases (Table B-3). To be conservative, the lowest U-crit, 3.02 BL/s, was selected as the minimum U-crit that the experimentally released steelhead would exhibit. Thus, it was assumed that the hatchery steelhead in this study could swim 3.02 BL/s for up to, but not more than, 2 minutes. The water temperatures that occurred at the HOR study area were impossible to determine definitively, but they generally were closer to 19°C than to 10.5 to 11.5°C. As a result, it seems plausible, that a U-crit for steelhead juveniles in this study may have been closer to 4.72 BL/s. (This value is similar to the sustained swimming speed used for Chinook salmon; see Table B-1.)

Table B-3
Steelhead Critical Swimming Speed, U-crit, for Juveniles

Fish Size (mm; length ± SE)	Water Temperature (°C)	Source	U-crit Body Lengths per Second (-2SE to +2SE)	U-crit Time Period (minutes)
109 ± 6.1 (TL ± SE) [1]	19	Hatchery	4.72 to 5.76	10
126 ± 0.5 (FL ± SE) [2]	10.5 to 11.5	Hatchery	3.02 to 4.34	2
148.6 ± 1.9 (FL ± SE) [3]	10.5 to 12	Hatchery	3.90 to 5.52	5

Notes: FL = fork length; SE = standard error of the mean; TL = total length; U-crit = critical swimming speed; mm = millimeters; °C = degrees Celsius
Values reported are Mean - 2 SE to Mean + 2 SE. The actual range of values was not available for all studies, and only SE could be determined for all three references to provide a directly comparable statistic.
Sources: [1] Myrick and Cech 2000; [2] Anderson et al. 1997; [3] Murchie et al. 2004

Juvenile steelhead emigrate to the Pacific Ocean from the Central Valley between November and late June, with a peak from early January through late March (Reclamation 2004) (Table B-4). Therefore, juvenile steelhead pass by the HOR study area mostly from November through June; These juveniles would be affected by any barrier at the HOR study area during this period.

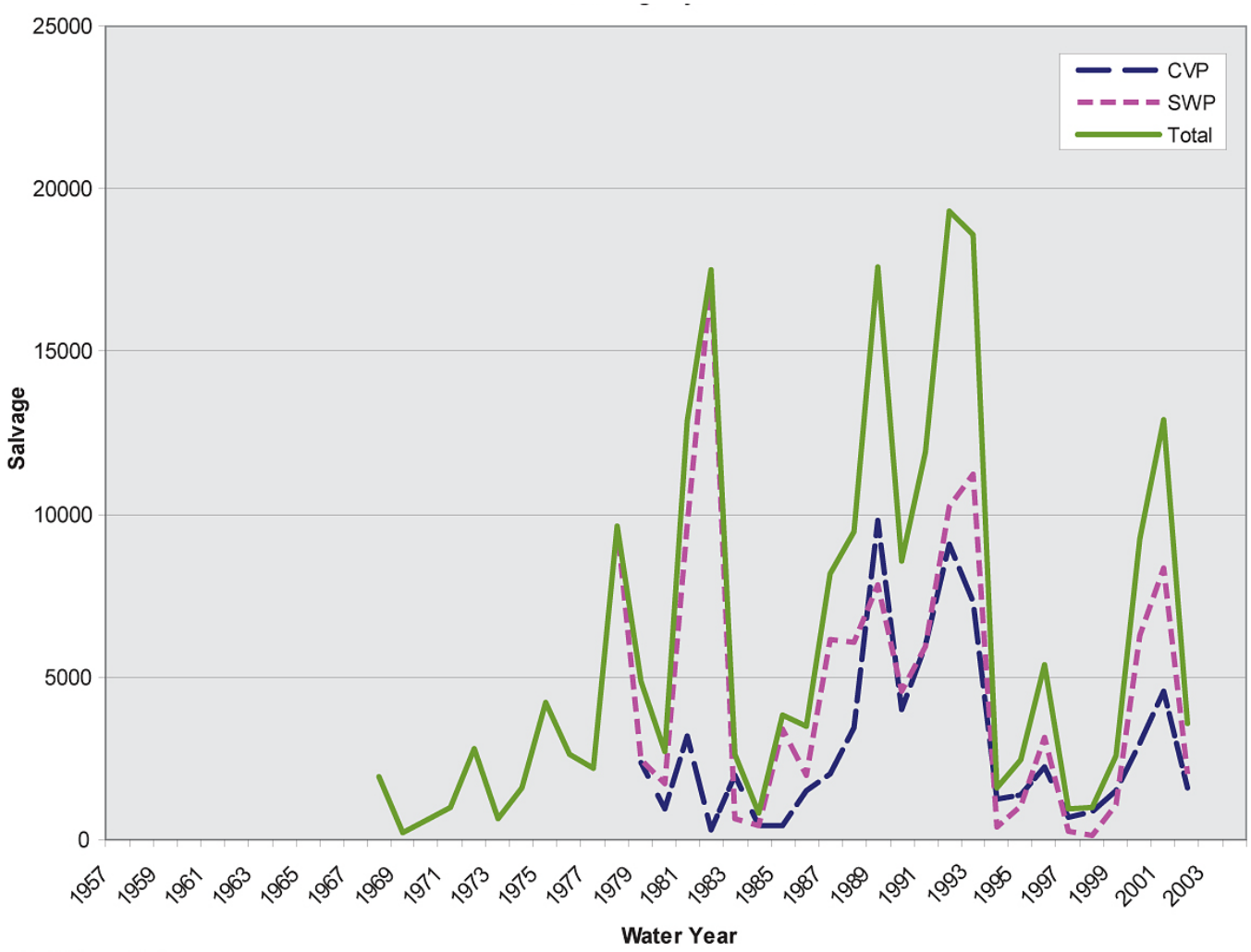
Table B-4
Dates of Steelhead Salvage January 1 through June 30
for 10 Years of Data Collected at the Skinner Delta Fish Protective Facility (Byron, California)

Year	First Salvage	Beginning Peak	End Peak	Last Salvage
2003	January 1	January 11	February 10	June 24
2004	January 6	February 15	March 2	May 19
2005	January 8	January 26	March 2	June 27
2006	January 4	February 18	April 11	June 28
2007	January 14	February 26	April 25	May 30
2008	January 25	February 15	March 1	June 10
2009	January 18	February 25	March 26	May 23
2010	January 19	February 7	March 10	June 27
2011	January 18	February 18	March 13	June 29
2012	January 5	March 29	April 18	June 3

Source: Present Study

Juvenile steelhead measuring 100 to 250 mm FL that are between 1 and 3 years old emigrate to the ocean (Moyle 2002; Reynolds et al. 1993). In coastal populations, juvenile steelhead migrate downstream at older than 1 year old and rear in the estuary for an additional 1 year before the onset smoltification. Some steelhead older than 1 year old moving down the Sacramento River are captured in rotary screw traps at Red Bluff Diversion Dam (RBDD), Glenn Colusa Irrigation District, and Knights Landing. These captures represent a large group of outmigrating juveniles that are experiencing the parr–smolt transition, and could theoretically spend some time rearing in the Delta. However, little information is available about use of the Delta by steelhead as rearing habitat (Stillwater Sciences 2006).

All species of fish using the Delta are affected by CVP and SWP operations (71 FR 834–862). The potential effects of water diversions on steelhead have not been comprehensively evaluated (McEwan 2001). However, pre-screen loss at Clifton Court Forebay is 82 to 87% (Clark et al. 2009). Steelhead are salvaged at the CVP and SWP, and the number salvaged varies depending on the year (Figure B-2).



0283507 002 SAC GRX

Source: Dan B. Odenweller, California Department of Fish and Wildlife

Figure B-2 Combined Number of Steelhead Salvaged from Tracy Fish Collection Facility (CVP) and Skinner Delta Fish Protective Facility (SWP)

B.2 OTHER SPECIES FOR PROTECTION AT HEAD OF OLD RIVER

B.2.1 DELTA SMELT

STATUS

The delta smelt (*Hypomesus transpacificus*) is endemic to the Sacramento-San Joaquin River Delta. Before 1970, it was undifferentiated from pond smelt, *Hypomesus olidus* (Moyle 2002). Until the early 20th century, delta smelt were common enough to be harvested commercially in the Delta (Bennett 2005). Delta smelt were listed as threatened under the federal and state ESAs in 1993. Between 1993 and 1999, some years saw a small rebound in delta smelt numbers. By 2002, populations of delta smelt, longfin smelt (*Spirinchus thaleichthys*), threadfin shad (*Dorosoma petenense*), and young striped bass (*Morone saxatilis*) were declining in the monitoring surveys. Sommer et al. (2007) hypothesized that poor stock size, habitat deterioration, increased winter entrainment, and zooplankton declines in rearing areas contributed to the decrease in the delta smelt population. Baxter et al. (2008)

specified these factors in the decline of delta smelt: fewer adults lead to reduced larval production, reduced food in the low-salinity zone, reduced size because of prey species changes, and increased winter entrainment. Bennett (2005) reported reduced food availability as one of the main causes for the decline of delta smelt. Various detailed analyses in recent years have supported some of the above factors as being of importance to delta smelt survival and abundance, and have also highlighted other factors such as increasing water clarity as being important (Mac Nally et al. 2010; Thomson et al. 2010; Miller et al. 2012; Rose et al. 2013a,b).

ADULT

Delta smelt are small translucent fish with large eyes. Adults typically have a fork length between 60 and 70 mm, but can reach lengths exceeding 120 mm FL (Moyle 2002). Most delta smelt complete their life cycle in 1 year, but some live for 2 years.

Delta smelt are found principally in Suisun Marsh and the Delta (Figure B-3) (Moyle et al. 1992). Most of the year, delta smelt are found around Suisun Marsh and Decker Island (Bennett 2005). Delta smelt have recently been recorded in the Sacramento Deep Water Ship Channel and may be using this area for spawning.Their distribution in the Delta is seasonal but does not appear to be determined by water temperature. Delta smelt can be found in water throughout a broad temperature range, but less than 25.4°C, their critical thermal maxima (Swanson et al. 2000).

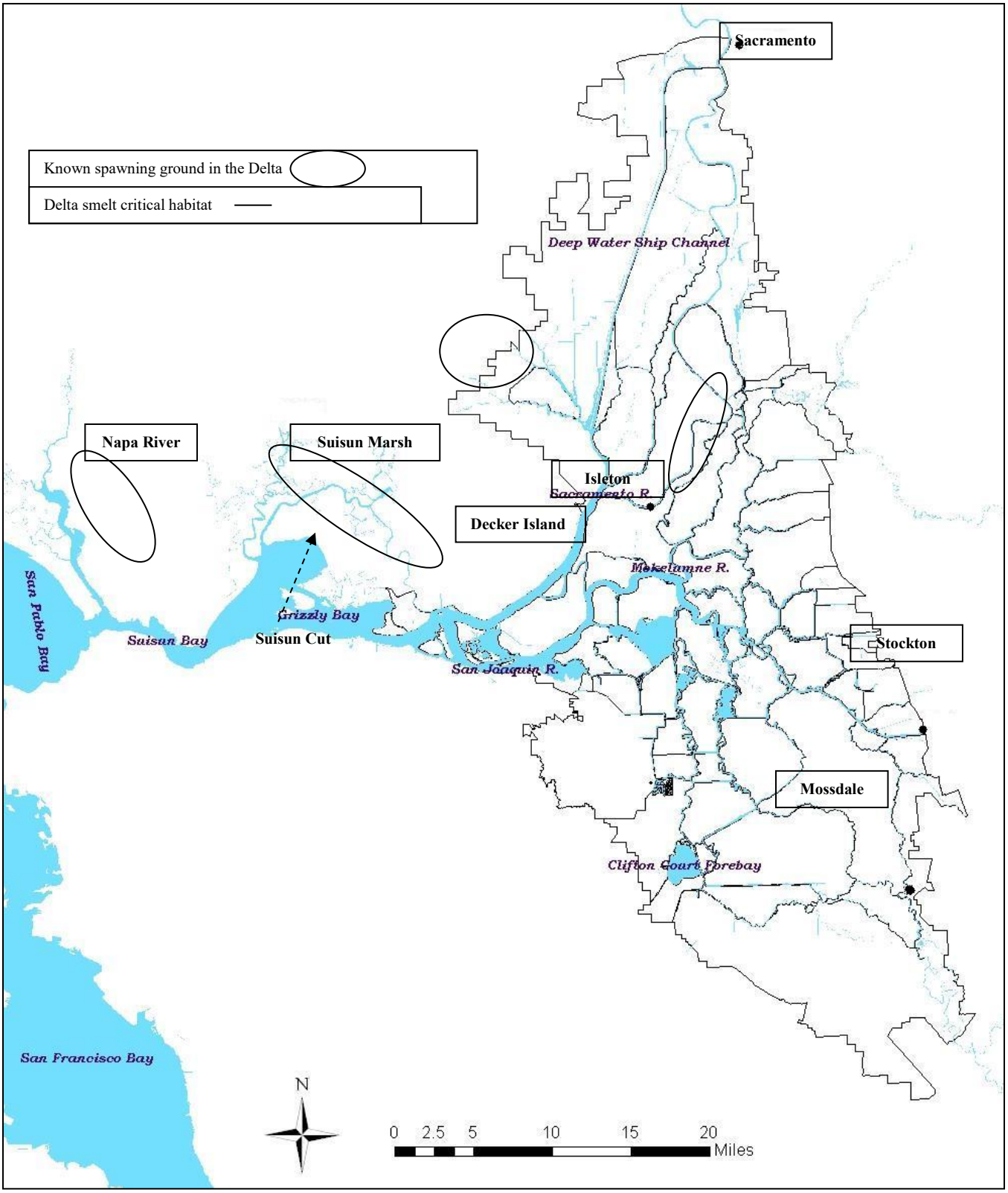
Delta smelt inhabit a broad range of salinities, from 0 to 18 practical salinity units (PSU). Delta smelt typically inhabits shallow waters (less than 3 m) with salinity of 18 PSU or lower (fresh to mesohaline). A salinity of 19 PSU (polyhaline) is lethal to delta smelt (Swanson et al. 2000). Most delta smelt are caught in water with salinity ranging from 0.2 to 2.0 PSU (fresh to oligohaline). These shallow areas are rich in zooplankton with hydraulic conditions that delta smelt seek to maintain position to improve feeding (Bennett 2005). This zone also is referred to as the Low Salinity Zone (LSZ). During high tide conditions, the LSZ can be found as far inland as 161 km (100 miles) upstream near the City of Sacramento on the Sacramento River. The LSZ also can be found as far west as the Carquinez Strait under high-flow conditions (Hobbs et al. 2006). Delta smelt abundance usually is centered a little upstream of the 2.0 PSU mark (Bennett 2005).These conditions are favorable for the prey of delta smelt, and thus, delta smelt remain near the LSZ. Delta smelt are poor swimmers, with a maximum burst speed of approximately 0.35 m/s (Cech, pers. comm., 2013). They usually swim in a short burst with a period of glide. This stroke-and-glide behavior may allow delta smelt to avoid predators.

The main prey for delta smelt historically was calanoid copepod (*Eurytemora affinis*) (Moyle et al. 1992). However, *E. affinis* has declined precipitously in the Delta attributed to the introduction of the clam (*Corbula amurensis*) by 1986[2] (Kimmerer et al. 1994). As *E. affinis* became rare, it was replaced in the delta smelt's diet by the copepod (*Pseudodiamptomus forbesi*). *P. forbesi* was observed for the first time in the San Francisco Bay estuary in 1987 (Carlton et al. 1990). However, *P. forbesi* also has experienced a precipitous decline, beginning at approximately the time of the arrival of the introduced copepod (*Limnoithona tetraspina*).

Since its introduction to the San Francisco Bay estuary in 1993 (Orsi and Ohtsuka 1999), *Limnoithona tetraspina* has become increasingly numerous (Bouley and Kimmerer 2006). This increase has occurred at the expense

[2] First record from Suisun Bay in October 1986.

of *P. forbesi*. Furthermore, *L. tetraspina* is less susceptible to predation by delta smelt. Thus, Bennett (2005) has concluded that this has reduced food availability and is one of the main causes for the decline of delta smelt.



Source: Data provided by California Department of Water Resources in 2013

Figure B-3[LR1] **Map of the Sacramento–San Joaquin Delta Showing Hypothesized Spawning Areas of Delta Smelt**

Delta smelt seldom were found in the stomach of predators, even when delta smelt were more abundant (Moyle 2002). The turbidity of the Delta, the transparency of delta smelt, and their burst-and-glide swimming behavior seem to be a good strategy to avoid predation (Moyle 2002).

Adults

Delta smelt migrate from the LSZ in the western Delta upstream to spawn from late February through May. The actual migration starts after the first winter flush of water due to rain in December, when the LSZ is farther downstream and turbidity is more than 12 Nephelometric turbidity units (NTU) (Grimaldo, pers. comm., 2013). Depending on the water quality conditions, both delta smelt spawning grounds and migration routes vary from year to year. For undetermined reasons, delta smelt migrate preferentially to the Sacramento River or the San Joaquin River in different years. Their selection of spawning location could be influenced by water quality (Moyle 2002). In those years when delta smelt migrate to the San Joaquin River to spawn, any movements from the south Delta upstream may change after construction of a barrier or delta smelt may be inhibited by the presence of a barrier at the divergence of the San Joaquin and Old rivers.

Many channels have been connected in the Delta to accommodate water distribution to irrigate agricultural lands. One of the major structural changes is that the Delta once had a dendritic structure, but many waterways are now linked (J. Burau, pers. comm., 2012). The Delta's current structure may allow increased numbers of delta smelt to become entrained at the CVP and SWP water export facilities from greater distances than would have occurred with the historic Delta dendritic structure.

The state managed Harvey O. Banks Pumping Plant and the federally managed Jones Pumping Plant, both located in the south Delta (Figure B-3), draw a large amount of water from the north Delta toward the south Delta for export. At times of high export, the net flow of rivers in the Delta can be negative, toward the diversion facilities, rather than positive, toward the ocean. The combinationof levee construction, interconnection of all Delta channels, and pumping plant export operations can lead delta smelt to be entrained at the pumps, increasing the probability of their mortality (Kimmerer 2008).

Delta smelt spawn February through June, with a peak around April (Moyle 2002). The spawning behavior of delta smelt is suspected to be triggered by a water temperature ranging from 14 to 18°C (Bennett 2005). Lunar cycles also are thought to be an important cue for spawning season (Moyle and Cech 1996). According to Hobbs et al. (2006), the suitable salinity for spawning is from 0 to 0.5 PSU (freshwater). At salinities exceeding 0.5 PSU, the suitability for spawning drops sharply. According to Bennett (2005), larger delta smelt may migrate earlier, and therefore, may spawn earlier and spawn more than once. No spawning area for delta smelt is known to exist upstream of the HOR study area (Figure B-3).

The preferred spawning habitat is not known, but based on the preferences of other smelt species, it may be sandy shoals (Sommer and Mejia 2013) like those located in the Sacramento Deep Water Ship Channel. Delta smelt release their eggs close to the substrate and rarely on vertical substrate (Bennett et al. 2002).

EGGS AND LARVAE

Females usually have approximately 1,200 to 2,600 eggs (Moyle et al. 1992). Fecundity increases with body length (Mager 1996), with a second-year smelt having three to six times as many eggs as a first-year smelt (Wang 2007).

Fertilized eggs are approximately 1 mm in diameter and likely adhere to the sandy substrate. Yolk-sac larvae hatch at 5.5 to 6.0 mm TL, 10 to 14 days after spawning. Early-hatching larvae can be from bigger delta smelt that can spawn early (Bennett 2005). These early-hatching larvae may be more likely to be entrained at the Banks and Jones pumping plants. This entrainment of early-spawned larvae may result in negative selection against the offspring of the larger, early-spawning females. Larvae are particularly vulnerable to pesticides. Furthermore, depending on the spawning location, larvae can rear in areas receiving agricultural or urban wastewater. The amount of pesticides in the water can be low, below a lethal dose, but the mixture of multiple pesticides and lengthy exposure can have sublethal effects (Kuivila and Moon 2004).

In the spring, water diversion is substantially reduced under the Vernalis Adaptive Management Program (VAMP). This reduction is executed to accommodate migrations by juvenile Chinook salmon. VAMP was created to reduce entrainment at the export facilities by helping migratory fish reach areas less influenced by the export pumping activities.

Ultimately, juvenile delta smelt need to reach the LSZ, where they can find advantageous feeding areas, although a portion of the population remains in productive upstream areas such as the Cache Slough complex year-round (Sommer et al. 2011a). Many delta smelt are carried to Suisun Bay by the first floods of spring. During this downstream migration period, they are vulnerable to entrainment at agricultural diversions or the pumps located in the south Delta. They also can be flushed into San Pablo Bay if the freshwater flow is very high, resulting in salinity related mortality. The larvae are attracted by light and swim close to the surface. The yolk sac is absorbed when the larvae reach a size of 6 to 7 mm TL, 4 to 5 days after hatching. Subsequently, the larvae become external feeders (Bennett 2005). At this early stage, delta smelt consume subadult cyclopoid and calanoid copepods (Nobriga 2002). At this stage, the growth rate of delta smelt is unknown in the wild (Bennett 2005). The high turbidity in which the first life stages exist suggests that feeding success is prey-density dependent. When they reach 10 to 15 mm TL, larvae feed on adult copepods (Nobriga 2002).

JUVENILES

The post-larval stage (15 to 20 mm TL) is reached 20 to 40 days after hatching, which typically is in June. The swim bladder usually is fully developed. This is when the fins are just starting to unfold (Bennett 2005).

Post-larval juveniles often are concentrated in Suisun Marsh close to the shore (Bennett 2005). In June, large schools of delta smelt can be found in Suisun Cut (Figure B-3), thought to be a critical nursery habitat (Hobbs et al. 2006).

Juveniles (20 to 50 mm FL) have a growth rate averaging 0.35 mm per day. Adult morphological characteristics appear when the fish reach 25 to 30 mm FL (Bennett 2005).

Delta smelt can be widely dispersed in the Delta, but usually are associated with the LSZ. Their swim bladder allows them to go up and down within the water column and stay in the LSZ. In Suisun Cut, delta smelt have a

reverse diel vertical migration. They are close to the surface during the day and more widely distributed in the water column at night. This behavior may lead to increased feeding success (Bennett et al. 2002).

By early September, delta smelt reach 55 to 70 mm standard length (SL) (Moyle 2002). By fall, they are fully grown. Between fall and February, most of the energy is allocated for gamete production.

Nobriga et al. (2013) found that there was no correlation between the abundance of juvenile striped bass and delta smelt survival, which could be attributed to relatively low spatial overlap of the two species or predation by striped bass always being sufficiently high to suppress the delta smelt population growth rate. According to Matica and Nobriga (2005), 27% of June and July inflows to the Delta are diverted for agricultural uses in the Delta. Most of these diversions pass through unscreened siphons, 20 to 46 cm in diameter, that draw water 60 to 90 cm above the channel bottom. These diversions may significantly affect the survival rate of delta smelt; however, analyses on the cumulative impact of these diversions on delta smelt remain unstudied, although Nobriga et al. (2004) noted that the low spatial overlap of delta smelt (generally occurring away from shore) with these diversions and the small hydrodynamic influence of these diversions led to low density of juvenile delta smelt in the entrainment samples they examined.

POTENTIAL BARRIER EFFECTS

Delta smelt are an indicator species for the health of the Sacramento-San Joaquin River-Delta. Delta smelt is a short-lived species of low fecundity. The species' life strategy is unusual and requires specific water quality and biotic conditions at certain times of the year to be successful. Delta smelt are highly adapted to the Delta's conditions; however, the Delta has changed considerably over the past 100 years. Delta waters are more consistently fresh and less similar to estuarine conditions and accommodate invasive species that are adapted to similar conditions in other systems. Two principal life stages are most vulnerable to direct influences by the operation of a fish barrier at the HOR study area. First, adult delta smelt must be able to migrate upstream from the area of the LSZ to spawning areas from winter through spring (generally December through March/April). Second, post-larvae and juveniles must be able to move from spawning areas back to the LSZ (generally March through June).

Delta smelt could be in the area of the HOR study area during their adult spawning migration and juvenile migration downstream to the LSZ. These life stages are most likely to be affected by the installation of a barrier at the HOR. As discussed previously, delta smelt are not known to spawn upstream of the HOR study area; thus, the potential impacts of a barrier are only hypothetical at this time.

B.2.2 GREEN STURGEON

STATUS

Few or no green sturgeon (*Acipenser medirostris*) have ever been recorded in the San Joaquin River (Adams et al. 2007), although white sturgeon (*A. transmontanus*) have been recently been documented to spawn in the lower San Joaquin River (Jackson and Van Eenennaam 2013). Because fish in the San Joaquin River have unimpeded access from the Sacramento River through the Delta, it is possible that green sturgeon may use the San Joaquin River, like white sturgeon. Therefore, the life history of green sturgeon and the potential effects of a barrier at the HOR on this species are discussed.

The population of green sturgeon that spawns in the Sacramento River is a member of the southern DPS[3] and was listed as threatened under the federal ESA in 2006[4] (Adams et al. 2007). In 2007, the California Fish and Game Commission adopted new regulations that made harvesting green sturgeon illegal. Although green sturgeon has little commercial value, it is a valuable species for traditional tribal fisheries and for the biodiversity of Pacific Northwest ecosystems. This anadromous fish is rare within the Delta, and population densities are sensitive to harvest (Heppell 2007). Little is known regarding green sturgeon's life history in and out of the Delta.

Adults

Green sturgeon is a long-lived species which exhibits bimaturation. Male smature earlier than females (Moyle 2002) at 13 to 18 years (152 to 185 cm TL), and females at 16 to 27 years (165 to 202 cm TL) (Beamesderfer et al. 2007). The maximum age is unknown, but Moyle (2002) hypothesizes that a maximum age of 60 to 70 years is possible. The maximum recorded ages for males and females, respectively, are 32 and 40 years at the Klamath River according to Beamesderfer et al. (2007).

Green sturgeon is the most marine-oriented sturgeon species, spending more time in the ocean than other members of the family Acipenseridae. Adults (greater than 150 cm TL) primarily are oceanic. NOAA (2005) postulated that green sturgeon may come into contact with polluted waters less often than white sturgeon because green sturgeon spends more time at sea. Adults can be found in inlets and bays along the West Coast, from Baja California to Alaska (Moyle 2002). However, the only adult tagged in San Pablo Bay proceeded out the Golden Gate immediately after tagging, strengthening the argument that adults are primarily ocean-going (Kelly et al. 2007).

In the ocean, green sturgeon disperses widely after outmigration from freshwater (Moyle et al. 1992). NOAA (2005) summarized results from acoustic tags, Oregon trawl books, and archival tags, showing that some green sturgeon make migrations as far north as Vancouver Island, Canada. During these saltwater migrations, green sturgeon commonly were found in water 40 to 70 m, and were never observed in water greater than 100 m in depth.

The adult green sturgeon diet includes small fish and benthic invertebrates such as shrimps, clams, and amphipods (Houston 1988; Moyle et al. 1992). Although no comprehensive assessment of the green sturgeon diet has been completed since that time, this diet could have changed; green sturgeon's common foods may have been replaced by the nonnative clam *Corbula amurensis*, established in the Delta by 1986. *C. amurensis* has become the most common food of white sturgeon, and also has been found in green sturgeon (DFG 2002).

Moser and Lindley (2007) suggested that adults may use the entire west coast of North America, but green sturgeon do not appear to reenter freshwater for any significant amount of time unless ready to spawn. In the San Francisco Bay-Delta, adults begin migrating into freshwater in late February. The spawning migrating southern DPS adults may encounter significant barriers. This DPS is suffering the loss of habitat in the Sacramento River, and some of this loss is caused by passage problems. During irrigation operations May 15 through September 15, Red Bluff Diversion Dam (RBDD) historically was a partial barrier and reduced upward migration of adult green

[3] A fish population is considered a DPS if it represents an ESU of a biological species. The fish stock must satisfy two criteria to be considered an ESU: (1) it must be substantially isolated reproductively from other population units and (2) it must represent an important component in the evolutionary legacy of the species (61 FR 61 4722, February 7, 1996).

[4] 71 FR 17757, April 7, 2006.

sturgeon (Brown 2007). Observations of spent adult green sturgeon have been made at RBDD (Brown 2007). Heublein (2006) reported that early green sturgeon migrants successfully passed RBDD and spawned. During the warmer months and when the Sacramento River is at low flow, water temperature increases and dissolved oxygen decreases. However, the swimming capacity of green sturgeon is not altered by water temperature up to 24°C (Allen et al. 2006) or by moderate hypoxia (Kaufman et al. 2006).

The Feather River is thought to be the most likely lost historical spawning habitat for green sturgeon (DFG 2002). Green sturgeon have been recorded in the Feather River as larvae caught in screw traps (Beamesderfer et al. 2004). Spawning has recently been recorded with eggs from three different sturgeon females (Van Eenenaam 2011). In spring 2011, many sturgeon adults were spotted while DIDSON surveys were being conducted (Seesholtz 2011). No juvenile green sturgeon have been documented in the San Joaquin River.

Green sturgeon are iteroparous, spawning every 2 to 5 years (Moyle 2002). The oldest females are estimated to spawn only eight times in their lifetime (Klimley et al. 2007). Spawning occurs from March through July, with peak activity April through June (Moyle 2002). Green sturgeon spawn in deep areas, or "holes," that are large, with turbulent and swift waters (0.8 to 2.8 m/s) (Moyle 2002; Parsley et al. 1993). Green sturgeon require specific spawning habitat, such as rocky substrates with crevices (Deng et al. 2002).

The Sacramento River has the only known spawning habitat for the southern DPS of green sturgeon (Moyle 2002). The main spawning area is thought to be between Hamilton City (river kilometer 320) and Keswick Dam (river kilometer 486) (DFG 2002) (Figure B-3). Heublein (2006) reports that Battle Creek is good spawning habitat for green sturgeon. The decline in green sturgeon abundance occurred after Keswick Dam was built, primarily because of the loss of spawning habitat located upstream (Moyle 2002).

Moyle (2002) suggests that green sturgeon may have reproduced in the San Joaquin River, because adult green sturgeon were captured at Santa Clara Shoal and Brannan Island State Recreation Area in the Delta. However, green sturgeon have not been documented in the San Joaquin River upstream of the Delta, and have not been observed in the river's tributaries (Beamesderfer et al. 2007; DFG 2002). The earliest available records noted green sturgeon as being "abundant in the [San Francisco] Bay and the rivers and creeks flowing into it" (Beamesderfer et al. 2007; Lockington 1879), but these reports do not specify green sturgeon locations. An impassible barrier (Friant Dam), high water temperatures, low discharges, possible entrainment, introduced species, poaching, pesticides, heavy metals, and poor water quality reduce the chance that green sturgeon could colonize the San Joaquin River (NOAA 2005).

Individual green sturgeon may emigrate after spawning, but many individuals aggregate in freshwater during summer before returning to the ocean in the fall (Belchik 2005). The largest known aggregation of green sturgeon in the Sacramento River is found near the Glenn Colusa Irrigation District's diversion intake (Heublein 2006). Green sturgeon appear to emigrate when temperatures fall below 10°C, generally after the first fall rainstorm (Erickson et al. 2002).

Green sturgeon tagged in spawning areas of the Klamath, Rogue, and Columbia rivers and Willapa Bay, Washington, with acoustic transmitters in 2002, 2003, and 2004 sustained migrations of 100 km per day. Rogue River fish tagged in 2002 returned in 2004, suggesting a minimal spawning periodicity of 2 years in the Rogue River watershed (NOAA 2005).

Eggs

Green sturgeon eggs require cold, well-oxygenated water. They spawn the largest eggs (with a mean diameter of 0.434 cm) of any sturgeon species (Cech et al. 2000). Females generate 60,000 to 140,000 eggs (Moyle 2002). The high degree of adhesiveness of its eggs allows green sturgeon to spawn in fast-moving water (Heublein 2006). The eggs incubate for approximately 6 days.

Larvae and Juveniles

After spawning and egg incubation, most larvae hatch at sizes between 0.8 and 1.9 cm TL (Emmett et al. 1991). Optimum temperatures for larval development are between 15° and 19°C (Mayfield and Cech 2004), but development can still occur at temperatures as low as 11°C (Van Eenennaam et al. 2005).

Juvenile green sturgeon (i.e., those less than 1.5 years of age, 75 cm TL, and 1.5 kg) are not physiologically ready for estuarine or oceanic emigration (Allen 2005; Allen and Cech 2007). In experiments with seawater treatments, 23% of juveniles less than 100 days post-hatch died because of starvation in the 33% salinity treatments (Allen and Cech 2007). Ten percent of the juveniles died in a second treatment with salinity of less than 3%. Allen and Cech's (2007) experiment showed that juveniles are more likely to survive if they spend some time in freshwater or the LSZ (e.g., the river or the Delta) before continuing to the ocean. Freshwater residence time is uncertain, but in the Klamath River, juvenile green sturgeon could spend between 1 and 4 years in freshwater and the estuary before entering the ocean (Nakamoto et al. 1995).

Exogenous feeding is correlated with the initiation of downstream migration (Moyle 2002). Based on trap samples at RBDD, downstream movements of juvenile green sturgeon occur from May through August at sizes between 2 and 6 cm (Gaines and Martin 2002). In riverine environments, juvenile green sturgeon are substrate-oriented and active at night (Kynard et al. 2005). In the Sacramento River watershed, juvenile green sturgeon swim down the Sacramento River and enter the Delta. The Delta is both a migratory route and a rearing ground. In the Sacramento–San Joaquin watershed, green sturgeon reach the ocean at approximately 1.5 years of age (Moyle 2002). They enter the ocean primarily during summer and fall (Emmett et al. 1991). Potentially, green sturgeon juveniles that use the Delta as a rearing area could come into contact with a barrier at the HOR study area.

Exogenous feeding begins 10 to 15 days after hatching when fish are 2.3 to 2.5 cm in length (Deng et al. 2002). Little is known about the diet of juvenile green sturgeon. The diet of green sturgeon changes as it grows; this is evident in the diet summary presented by the California Department of Water Resources (DWR 2003). In the Delta, small juveniles eat opossum shrimp (*Neomysis mercedis*) and amphipods (Radtke 1966). Then, as they grow, green sturgeon eat invertebrates such as clams, shrimps, and crabs associated with the demersal habitats that they frequent. As adults, green sturgeon eat the previously described demersal invertebrates and demersal fish (Kohlhorst 2001).

During downstream migration by juvenile green sturgeon they can be entrained at the SWP and CVP water diversion facilities and their associated fish salvage facilities, the Skinner Delta Fish Protective Facility (SFPF) and Tracy Fish Collection Facility (TFCF). Before 1986, SFPF caught an average of 732 green sturgeon per year. After 1986, the annual average fell to 47. At TFCF, 889 green sturgeon were salvaged per year before 1986, and 32 per year after 1986. Green and white sturgeon may not have been differentiated before 1986. However, large

decreases apparently occurred at SFPF between the mid-1970s and 1986, and at TFCF during the mid-1980s (NOAA 2005). The decline in green sturgeon continues with fewer fish entrained each year (fewer than 10 individuals annually) at state and federal fish facilities (DFG 2002). For example, between 1993 and 1997, seven green sturgeon were caught at SFPF and TFCF.

In freshwater, juvenile green sturgeon are subject to predation from invasive species. For example, in July 2000, two juvenile green sturgeon (each approximately 10 cm long) were regurgitated from two smallmouth bass (*Micropterus dolomieu*) that were caught on the Umpqua River in Oregon (NOAA 2005).

Substrate composition has a significant effect on larval green sturgeon growth, according to Nguyen and Crocker (2007). Green sturgeon larvae prefer flat and smooth surfaces, such as slate rock. Nguyen and Crocker (2007) also noticed that green sturgeon larvae typically are photosensitive. In their native environment, slate rock-like surfaces can provide cover from light and predators. Sand and cobble substrates seem to be lethal for these exogenous feeders. The green sturgeon feeds by suctioning river substrate (Nguyen and Crocker 2007). Sand can affect their digestive system. Also, the larvae can become trapped between cobbles.

Subadult

Subadult (sexually immature) green sturgeon are more than 1.5 years old and 75 cm TL, but less than 15 years old and 150 cm TL. At this age, subadult green sturgeon enter the ocean or remain in the estuary to feed and grow. Kelly et al. (2007) indirectly showed that subadult green sturgeon may use the San Francisco Bay estuary as a feeding ground. Kelly et al. (2007) tagged four subadult green sturgeon in San Pablo Bay and tracked them for 12 months. These four sturgeon remained in San Pablo Bay for the entire tracking study. Kelly et al. (2007) recorded movements characteristic of foraging behavior. Summer concentrations in coastal estuaries may indicate feeding aggregations or thermal refugia (Beamesderfer et al. 2007; Moser and Lindley 2007). Moser and Lindley (2007) hypothesized that green sturgeon improve their growth rates in summer by foraging in the relatively warm, saline waters of Willapa Bay, Washington. Green sturgeon may use San Pablo Bay, where they are found in unusual numbers, because San Pablo Bay's warm water is similar to that of Willapa Bay (Beamesderfer et al. 2007).

The data from salvaged fish at SFPF and TFCF are the only data available on green sturgeon, and cannot be used to examine population size (Beamesderfer et al. 2007) because of limitations in how these data were collected. However, Beamesderfer et al. (2007) described a hypothetical population structure for green sturgeon, with the majority of the population (63%) represented by subadults from age 1.5 to 15 years old. If true, the main threat to their continued existence could reside in the estuaries in the summer where these subadult fish spend substantial time.

Potential Barrier Effects

Long lifespan, delayed maturation, large body size, high fecundity, iteroparity, and anadromy are life-history traits of the green sturgeon. These traits do not lend themselves toward overcoming the challenges (predation, entrainment, and introduced species) at the HOR study area. Juveniles may spend an appreciable duration of time in the Delta, but are difficult to study because they do not seem to school. Therefore, identifying local threats and vulnerabilities in the Delta and estuary can be difficult. The principal threats to green sturgeon in the Delta are thought to be pollution, loss of habitat, and entrainment at water diversion systems. Subadults may use the warm summer waters in San Pablo Bay to achieve higher growth rates than in cooler habitats. Because of the lack of

data, a complete and accurate picture of the life history of green sturgeon is not possible. Specifically, more information is needed to get a complete picture of the green sturgeon's life history should it be determined that green sturgeon do occur in the San Joaquin River. Until then, the potential impact of a barrier at the HOR study area on green sturgeon is hypothetical.

B.3 FOCAL PREDATORY FISH SPECIES

B.3.1 STRIPED BASS

Striped bass is an anadromous, iteroparous fish native to the eastern United States (St. Lawrence River to Louisiana) and introduced into the San Francisco Bay estuary in 1879 (Dill and Cordone 1997). A commercial fishery for striped bass was established within 10 years of introduction and continued until the fishery was closed in 1935 due to an observed severe population decline in the San Francisco Bay estuary. The commercial fishery maintained annual catches averaging 660,000 pounds in the fishery's final decade (Skinner 1962, as cited by Dill and Cordone 1997). The sport fishery developed more slowly than the commercial fishery. By the late 1960s, it became extremely popular, and constituted approximately 60% of the angling dependent on the San Francisco Bay estuary, including the ocean and river Pacific salmon fisheries (Chadwick 1968, as cited by Dill and Cordone 1997). Population estimates for striped bass are problematic as the portion of the population inhabiting the ocean remains unstudied and current estimates are based upon fish counted in the rivers and estuary only. Adult striped bass are commonly caught off beaches from Monterey Bay to San Francisco. Recent studies have shown that subadult striped bass also emigrate to the ocean (LeDoux-Bloom 2012).

The adult striped bass population (males age 2 and older and females age 4 and older) was estimated at between 2.3 and 3 million fish in the early 1960s (Dill and Cordone 1997). Adult abundance declined from the 1960s to the late 1980s/early 1990s, at which point female abundance was estimated by modeling at 500,000 fish and male abundance was 300,000 to 400,000 fish (Loboschefsky et al. 2012). Subsequent abundance from the mid-1990s to mid-2000s was higher. The abundance of subadult striped bass (males younger than age 2 and females younger than age 4) was estimated to be highly variable (4 to 15 million fish) between 1981 and 2003; age 2 abundance doubled in the mid- to late 1990s (Loboschefsky et al. 2012).

Striped bass are epipelagic, opportunistic feeders, and prey changes with life stage and season. Juvenile and older striped bass prey upon fish and invertebrates. Striped bass prey selection has not been studied in the Pacific Ocean. Modeling has estimated the total annual consumption of prey fish by striped bass (age 3 and older) between 1969 and 2004 in the San Francisco Bay-Delta watershed ranged between approximately 8,200 metric tons in 1994 and approximately 30,500 metric tons in 1972 (Loboschefsky et al. 2012). Annual total consumption of prey fish by subadult striped bass (those ages 1 and 2) between 1981 and 2003 was estimated to have varied between approximately 2,000 metric tons in 1988 and approximately 19,000 metric tons in 1999/2000 (Loboschefsky et al. 2012).This estimate may be high as subadults are known to consume mainly benthic invertebrates during this life stage.

The abundance of young-of-the-year striped bass collected in the Fall Midwater Trawl survey conducted by the CDFW has declined considerably over time. It is unknown why this has occurred based on the lack of a similar decline in adult abundance (Baxter et al. 2010). Factors related to the decline in young-of-the-year abundance may include changes in summer food availability, fall Delta outflow, water clarity, and low adult abundance (MacNally et al. 2010; Thomson et al. 2010).

A long-term shift of smaller striped bass distribution into shallower areas may have occurred, which decreased the number of the species available for capture in survey trawls (Sommer et al. 2011). Telemetry studies of subadult striped bass have shown seasonal shifts in habitat use in winter and spring associated with changing water temperature and schooling behavior based on salinity and possibly the onset of sexual maturity (LeDoux-Bloom 2012). Seasonal habitat preference may influence predation rates and create seasonal predation hotspots. Of particular relevance at the HOR study area is the overlap of adult upstream migration periods with the downstream migration period of juvenile salmonids when water temperature exceed 15°C.

Based on catch composition from angling studies (e.g., DWR 2012), striped bass appear to be the main transitory predatory fish species at the HOR study area and elsewhere in the Delta, at least during the main months of interest for outmigrating juvenile salmonids (late winter through late spring). The effects on trends in the populations of native fish species from striped bass predation have received some study. Using a modeling approach, Lindley and Mohr (2003) suggested that increases in the abundance of adult striped bass could appreciably increase the probability of extinction of winter-run Chinook salmon. No support exists for abundance of adult striped bass (combined with water clarity) as a factor influencing trends in delta smelt abundance (Maunder and Deriso 2011; Miller et al. 2012). The main biological and ecological characteristics of striped bass are summarized in Table B-5.

B.3.2 LARGEMOUTH BASS

Largemouth bass is a freshwater native from the eastern United States. Largemouth bass was introduced into California's Central Valley in the 1890s (Dill and Cordone 1997) and was present in the Delta shortly thereafter (Baxter et al. 2010). Abundance in the Delta has increased considerably over the past several decades, at the same time as an increase in coverage of the naturalized and invasive submerged aquatic plant species *Egeria densa*,[5] with which largemouth bass are associated (Baxter et al. 2010; Brown 2003). The Delta now is rated as one of the top ten fishing locations in the United States for the centrarchid basses, including largemouth bass (Hall 2013)

Largemouth bass switch to piscivory at smaller sizes than do striped bass and other predatory fish species such as Sacramento pikeminnow and catfishes. Largemouth bass consume a larger number of native fish species than striped bass (Nobriga and Feyrer 2007). Studies about the potential effect of largemouth bass on the native fish population are ongoing. Some early analyses show evidence of negative effects of largemouth bass on native fishes (e.g., MacNally et al. 2010; Maunder and Deriso 2011) while others do not (Miller et al. 2012). The main biological and ecological characteristics of largemouth bass are presented in Table B-6.

B.3.3 CHANNEL CATFISH

Channel catfish (*Ictalurus punctatus*) is a freshwater native to central U.S. drainages and northern Mexico. The population in California's Sacramento River area is likely the result of planting that occurred in the American River in the 1920s (Dill and Cordone 1997). Channel catfish are omnivorous, scavengers and consume fish prey as part of their diet (Moyle 2002). A summary of channel catfish biological and ecological characteristics is presented in Table B-7.

[5] Commonly referred to as Brazillion waterweed, large0flowered waterweed, or *Elodea.*

B.3.4 WHITE CATFISH

White catfish (*Ameiurus catus*) is a freshwater native to the U.S. Atlantic coastal states and was introduced into the San Joaquin River at Stockton in 1874 (Dill and Cordone 1997). White catfish spread rapidly following introduction, and provided a significant portion of the 200,000- to 700,000-pound-per-year commercial catfish fishery that developed in the Delta before the fishery was closed in 1953 as a result of overfishing concerns (Dill and Cordone 1997).

Catfish constitute one of the most popular inland sport fisheries in California (Dill and Cordone 1997). The population in the south Delta is relatively slow growing, possibly the result of high density and low prey availability (Schaffter 1997). White catfish are omnivorous scavengers and their diet includes fish (O'Rear 2012). O'Rear (2012) studied the dietary habits of white catfish in Suisun Marsh and the relative potential effects on native fishes. He concluded that white catfish do not eat fishes targeted for conservation and much of the food they eat is either not utilized by at-risk or commercially important fishes or is unlikely to be limiting. Consequently, white catfish appear to be relatively harmless to populations of other fishes in Suisun Marsh. Predation on fish by white catfish appeared to occur only when water management of wetlands made such predation feasible. O'Rear (2012) suggested that high production of fish and invertebrates in managed wetlands could contribute to a larger population of white catfish in Suisun Marsh in the future, and that such a population increase could pose more of a threat to fish species of conservation concern. A summary of the main biological and ecological characteristics of white catfish are provided in Table B-8.

Table B-5
Main Biological and Ecological Characteristics of Striped Bass

Maximum Size and Age	Size By Age	Diet and Other Feeding Characteristics	Primary Habitat and Environmental Conditions	Migratory Behavior	Intraspecific Associations	Reproduction
125 cm FL (41 kg), >30 years (Moyle 2002)	First year: 9–11 cm FL Second year: 23–30 cm FL Third year: 28–40 cm FL Fourth year: 44–54 cm FL Growth of 5–10 cm/year thereafter (Moyle 2002) Assumed sizes at age in bioenergetics modeling by Loboschefsky et al. (2012): 1: 172 mm FL 2: 254 mm FL 3: 448 mm FL 4: 537 mm FL 5: 611 mm FL 6: 680 mm FL (Loboschefsky, pers. comm., 2013)	Age 1: 12% fish, 88% other (by volume) Age 2: 82% fish, 18% other (by volume) Age 3+: 99% fish, 1% other (by volume) (values assumed by Loboschefsky et al. 2012) Epipelagic opportunistic feeders that consume most possible prey types, including fish such as American and threadfin shad, juvenile striped bass, and juvenile salmonids (Moyle 2002; Tucker et al. 1998)	Pelagic (Moyle 2002); temperature tolerance 7.2° to 27°C, salinity 0–33.7 ppt, current velocity tolerance 0–500 cm/s and optimum 0–100 cm/s (Hassler 1988); intolerant of poor water quality conditions and low oxygen; inhabit water temperatures above 16°C when available (LeDoux-Bloom 2012).	Subadults (~23–42 cm FL) in the Bay-Delta watershed have three main residency patterns: riverine (freshwater), low-salinity zone (0.5 to 10 ppt), and bay (10–30 ppt) (LeDoux-Bloom 2012). Riverine residents from the Sacramento/American Rivers move to the south Delta (Clifton Court Forebay) in fall, and then return upstream to the rivers in spring. Subadults emigrate to the ocean in winter and return to the bays and rivers in late spring (LeDoux-Bloom 2012). Adults generally move into freshwater from San Pablo and San Francisco Bays in fall, and many overwinter in the Delta before a spring upstream spawning migration and return to the bays thereafter (Moyle 2002; LeDoux-Bloom 2012).	Gregarious (Moyle 2002)	Spawn in freshwater mostly from mid-April to mid-June (Hassler 1988). No spawning occurs below 14°C, optimum temperature is 15° to 20°C, and spawning ceases at >21°C (Moyle 2002). Most San Joaquin River spawning occurs from Venice Island to Antioch, and farther upstream in high-flow years (Moyle 2002). Females typically first spawn at 4–6 years (45 cm FL), and males mostly first spawn at 2–3 years (25 cm FL) (Moyle 2002).

Notes: °C = degrees Celsius; Bay-Delta = San Francisco Bay/Sacramento–San Joaquin Delta; cm = centimeters; FL = fork length; kg = kilograms; cm/s = centimeters per second; mm = millimeters; ppt = parts per thousand

Table B-6
Main Biological and Ecological Characteristics of Largemouth Bass

Maximum Size and Age	Size By Age	Diet and Other Feeding Characteristics	Primary Habitat and Environmental Conditions	Migratory Behavior	Intraspecific Associations	Reproduction
76 cm TL (10.5 kg), 16 years (Moyle 2002)	First year: 5–20 cm Second year: 7–32 cm Third year: 15–37 cm Fourth year: 20–41 cm (Moyle 2002)	Generally subsist on fish when greater than 100–125 mm SL (Moyle 2002). Fish greater than 150 mm FL have high probability of having fish in stomachs (Nobriga and Feyrer 2007). Fish consumed in older studies included threadfin shad, Chinook salmon, bluegill (*Lepomis macrochirus*), and black crappie (*Pomoxis nigromaculatus*) (Turner 1966a). Bullfrogs (*Lithobates catesbeiana*) formed more than 50% of diet in specimens examined by Turner (1966a). Fish consumed in San Joaquin River downstream of Old River in 2008–2010 included juvenile largemouth bass; threadfin shad; shimofuri gobies (*Tridentiger bifasciatus*); western mosquitofish (*Gambusia affinis*); and unidentified gobies, sunfish, and catfish (Conrad, pers. comm., 2013). Active during most of day and moonlit nights, intense foraging at dusk, most efficient foraging in low to moderate light (Moyle 2002). Feeding rate decreases with increasing turbidity (Ferrari et al. 2013; Huenemann et al. 2012).	Tolerate poor water quality conditions: can survive water of 36°–37°C and dissolved oxygen down to 1 milligram per liter (Moyle 2002). Optimal growth at 25°–30°C, with adults preferring 27°C (Moyle 2002). Usually found in waters with salinity <3 ppt and avoid salinities >5 ppt in California (Moyle 2002). Generally found close to shore in areas with lower flows (optimally <6 cm/s, unsuitable at >20 cm/s) (Stuber et al. 1982); individual adults may remain in restricted areas close to structures (submerged rocks or woody debris) or wander widely (Moyle 2002).	Spring migrations to areas with suitable spawning habitat may occur within river systems (e.g., movements in excess of 5 km) (Goclowski et al. 2013).	Solitary as adults, school as juveniles (Moyle 2002).	Spawn into nests created and guarded by males in sand, gravel, or debris-littered bottoms, often next to submerged objects (e.g., logs and boulders) in shallow waters (0.5 to 2 m) (Moyle 2002). Nest-building begins at 15°–16°C (March/April), and spawning continues up to 24°C (June). First spawning at 18–21 cm TL (males) and 20–25 cm TL (females) in second/third year (Moyle 2002).

Notes: °C = degrees Celsius; cm = centimeters; FL = fork length; kg = kilograms; cm/s = centimeters per second; mm = millimeters; ppt = parts per thousand; TL = total length; SL = standard length

Table B-7
Main Biological and Ecological Characteristics of Channel Catfish

Maximum Size and Age	Size By Age	Diet and Other Feeding Characteristics	Primary Habitat and Environmental Conditions	Migratory Behavior	Intraspecific Associations	Reproduction
>100 cm TL (>26 kg), nearly 40 years; in California fish more than 53 cm TL (2.5 kg), 10 years are unusual (Moyle 2002).	In good habitat: First year: 7–10 cm TL Second year: 12–20 cm TL Third year: 20–35 cm TL Fourth year: 30–40 cm TL Fifth year: 35–45 cm TL (Moyle 2002)	Omnivorous, including mostly invertebrates and fish (Moyle 2002). Piscivory begins at larger size (30–38 cm TL) (Moyle 2002), with fish in diet of larger catfish found to be 11% of stomach volume in Clifton Court Forebay (Edwards 1995) and 25% in the Delta as a whole (Turner 1966b). Fish species consumed in Clifton Court Forebay included striped bass and threadfin shad (Edwards 1995). Feed at night in faster water (Moyle 2002).	Main channels of large streams, with adults spending daytime in pools or beneath logjams/undercuts, then moving into faster water to feed at night (Moyle 2002). Optimal midsummer water temperatures in pools/backwaters/littoral areas for adults are 26°–29°C; maximum salinity in summer is optimal at approximately 1 ppt or lower, and suitability is zero at around 12 ppt (McMahon and Terrell 1982). Tolerant of a wide variety of environmental conditions, such as low dissolved oxygen (Moyle 2002).	Studies in other systems have demonstrated both migration and homing of channel catfish (e.g., occupation of relatively small home ranges in summer followed by migration downstream in fall, then return upstream to spawn in spring in the lower Wisconsin River) (Pellett et al. 1998).	Schooling has been observed for a number of weeks in stocked hatchery-reared channel catfish, with schools breaking up following a period of high flow/turbidity (Siegwarth and Johnson 1998).	Variable size/age at maturity, but typically at least 30 cm TL (>3 years) (Moyle 2002). Spawning at 21°–29°C (26°–28°C is optimal) (Moyle 2002). Cave-like sites used for nesting (e.g., old muskrat burrows, undercut banks, logjams, riprap) (Moyle 2002). Males aerate their nests (Moyle 2002).

Notes: °C = degrees Celsius; cm = centimeters; kg = kilograms; ppt = parts per thousand; TL = total length

Table B-8
Main Biological and Ecological Characteristics of White Catfish

Maximum Size and Age	Size By Age	Diet and Other Feeding Characteristics	Primary Habitat and Environmental Conditions	Migratory Behavior	Intraspecific Associations	Reproduction
>60 cm TL (>3 kg), but fish >2 kg are unusual (Moyle 2002).	Average for first 8 years of life in south Delta: First year: 125 mm FL Second year: 163 mm FL Third year: 192 mm FL Fourth year: 214 mm FL Fifth year: 229 mm FL Sixth year: 243 mm FL Seventh year: 258 mm FL Eighth year: 272 mm FL (Schaffter 1997)	Carnivorous bottom feeders, occasionally at surface to feed on planktivorous fishes (Moyle 2002). Wide variety of bottom-oriented food items, including invertebrates (amphipods and opossum shrimp). Percentage of diet made up by fish is variable: 40% (Turner 1966b), 4% (Edwards 1995), 20% (O'Rear 2012). Fish species consumed included sculpin *Cottus* spp.) in Clifton Court Forebay (Edwards 1995), and threespine stickleback (*Gasterosteus aculeatus*), prickly sculpin (*Cottus asper*), shimofuri goby, yellowfin goby (*Acanthogobius flavimanus*), western mosquitofish, and rainwater killifish (*Lucania parva*) in Suisun Marsh (O'Rear 2012).	Most abundant in slow-current areas; avoid shallow areas (<2 m) by day but move into them by night; tolerate salinity of 11–14.5 ppt, but not present in Suisun Marsh at >8 ppt (Moyle 2002). Usually found in water that is >20°C in summer, and tolerate 29°–31°C (Moyle 2002).	No regular seasonal migrations; aggregate in deepest parts of channels in winter, and disperse more widely in warmer months (Moyle 2002).	Aggregate in deeper parts of channels (Moyle 2002).	Mature at 20–21 cm FL, with spawning at >21°C (mostly June–July) (Moyle 2002). Nests built by males on sand, gravel, near cover, or caves made by rocks (Moyle 2002). Males care for the young (Moyle 2002).

Notes: °C = degrees Celsius; cm = centimeters; FL = fork length; kg = kilograms; mm = millimeters; ppt = parts per thousand; TL = total length

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APPENDIX C

Comparisons Using HTI- and VEMCO-Derived Data

C.1 INTRODUCTION

Two primary acoustic telemetry manufacturers design equipment that was used or evaluated in the current study: Hydroacoustic Technology, Inc. (HTI) (Seattle, Washington) and VEMCO (Bedford, Nova Scotia, Canada). For this report, HTI acoustic transmitters, receivers, and software were used to collect behavioral information in the form of two-dimensional (2D) data (position information obtained using two or more hydrophones at a time). In contrast, VEMCO acoustic transmitters and receivers were used by the Six-Year Steelhead Study (6YSS) team to collect survival information in the form of one-dimensional data (position information obtained using one hydrophone at a time). The fact that juvenile salmonids with VEMCO transmitters were passing through the Head of Old River (HOR) study area in 2012 during the experimental period provided an opportunity to compare the utility of these two technologies for our study purposes.

The HTI gear used in 2012 was used for hydrophone deployment, which is described in Section 5.1.3, "Acoustic Telemetry Assessments." Thirteen hydrophones were used to provide 2D tracks upstream and downstream of the physical rock barrier (Figure 5-4).

The VEMCO gear used in 2012 consisted of four sets of hydrophones deployed around the HOR study area:

- one hydrophone, VEMCO-HOR-U (Figure 5-13), was approximately 650 meters (m) upstream of the HTI San Joaquin River (SJR) start line;
- one hydrophone, VEMCO-HOR-W (Figure 5-13), was approximately 64 m upstream of the HTI SJR start line;
- four hydrophones were deployed downstream of the HTI SJR finish line, the furthest of which was 554 m downstream and defined the VEMCO SJR finish line; and
- four hydrophones were deployed downstream from the HTI Old River finish line, the furthest of which was 860 m downstream and defined the VEMCO Old River finish line.

Decisions about further monitoring and research in the south Delta would benefit from knowing whether data collected using these two types of equipment were comparable and which type of equipment would be an appropriate fit for a planned study. Thus, the primary objective in collecting and analyzing data with VEMCO equipment was to determine whether there was any observed difference between VEMCO- and HTI-derived data.

The one measure of barrier efficiency that was determined using both HTI and VEMCO gear was overall efficiency (O_E) for juvenile Chinook salmon in 2012 (See Table C-1, hypothesis $HC1_0$). Juvenile Chinook salmon O_E (see Equation 5-1 in Chapter 5, "Methods") was the number of tags inserted into juvenile Chinook salmon and released at Durham Ferry that were determined to have passed by the HOR study area and continued down the San Joaquin River, divided by the total number of tags that arrived at upstream HOR study area hydrophones (Figure 5-13). A similar calculation was made with juvenile steelhead using tags inserted into juvenile steelhead and released at Durham Ferry.

Table C-1
Objectives and Hypotheses Related to Juvenile Salmonid Routing Including Barrier Effects, as Derived from VEMCO and HTI Equipment

Year and Treatment	Objective	Hypothesis Number	Hypotheses
2012 Physical Rock Barrier	Determine whether, for 2012, the overall efficiency derived from tagged juvenile Chinook salmon with HTI acoustic transmitters was the same as the overall efficiency derived from tagged juvenile Chinook salmon with VEMCO transmitters.	$HC1_0$	Rock barrier overall efficiency estimated from VEMCO gear was equal to the overall efficiency estimated from HTI gear for juvenile Chinook salmon.
	Determine barrier efficiency in 2012 using VEMCO gear.	$HC2_0$	Overall efficiency was the same for juvenile Chinook salmon and juvenile steelhead.

Source: Data compiled by Turnpenny Horsfield Associates and AECOM 2013

Comparisons of treatments (barrier/years) for juvenile Chinook salmon O_E using HTI-derived gear are presented in Section 6.1.8, "Comparison Among Barrier Treatments from 2009 (BAFF On), 2010 (BAFF On), 2011 (No Barrier), and 2012 (Rock Barrier)," in Chapter 6, "Results." In this appendix, these HTI-derived O_E observations are compared with VEMCO-derived O_E observations.

In 2012, juvenile Chinook salmon and steelhead were surgically implanted with VEMCO transmitters. This allowed a direct comparison of the physical rock barrier effectiveness between species (Table C-1, hypothesis $HC2_0$). However, for HTI-derived data in 2012, no comparison between species could be made because only five juvenile steelhead were detected through the HTI hydrophone array. The sample size was too small to allow valid hypothesis testing or analysis.

Transit speed was the other measure of behavior efficiency determined with both HTI and VEMCO gear for juvenile Chinook salmon in 2012. Transit speed for a tagged juvenile salmonid was the distance traveled from an upstream detection point to a detection point downstream from the divergence in either the San Joaquin or Old rivers, divided by the amount of time the tag took to travel that distance. See Appendix D, "Transit Speed Analysis," for a discussion on transit speed.

C.2 METHODS

C.2.1 VEMCO EQUIPMENT SPECIFICATIONS

Two hatchery sources were used to provide the juvenile Chinook salmon and steelhead in 2012 (Table C-2). The juvenile Chinook salmon that received VEMCO tags had a different size range but were from the same hatchery (Merced River Fish Hatchery) as the fish that received HTI tags (Tables 5-1 and C-2). The juvenile steelhead that received VEMCO tags had a different size range than the fish that received HTI tags (Tables 5-1 and C-2). The hatchery production methods for the juvenile Chinook salmon and steelhead used in the study were the same for both VEMCO and HTI and described in Appendix B, "Focal Fish Species Information." In 2012, the target tag burden was seldom exceeded (Table C-3).

Table C-2
Juvenile Salmonids Used for Head of Old River Barrier Evaluations with VEMCO Gear

Study Year	Species	Hatchery	Run	Total Number Released	Minimum size (mm TL)	Maximum size (mm TL)
2012	Chinook Salmon	Merced River Fish Hatchery	Fall	961	100	199
2012	Steelhead	Mokelumne River Fish Hatchery	Winter	1,435	115	316

Notes: mm = millimeter; TL = total length.
Source: Israel, pers. comm., 2013

Table C-3
Range of VEMCO Tag Burdens Experienced by Juvenile Salmonids

Study Year	Model Number	Percent Tag Burden			Percentage of Tags Exceeding 5% of Body Mass	Species
		Minimum	Mean	Maximum		
2012	V5	0.020	0.038	0.054	3.5	Chinook Salmon
2012	V6	0.003	0.009	0.030	0.0	Steelhead

Source: Data compiled by Turnpenny Horsfield Associates 2013

In 2012, Model V5 tags inserted into juvenile Chinook salmon and Model V6 tags inserted into the juvenile steelhead (Table C-4) had newly available coding from VEMCO. The first type of coding was typical VEMCO coding with Pulse Period Modulation (PPM), which allowed each tag to produce a unique series of pulses in a transmission sequence that lasted 3–5 seconds. A 30-second nominal delay occurred (although the exact amount of time ranged randomly from 20 to 40 seconds) before subsequent transmissions. This first type of coding was detected at all locations except at the Tracy Fish Collection Facility (TFCF) and Skinner Delta Fish Protective Facility (SFPF) in the southwest Delta. The second type of coding, which was used at the TFCF and SFPF, was a newly available High Residency/PPM (HR/PPM) transmission alternated with the PPM transmission. This HR/PPM transmission was similar to the PPM. Thus, there were two codes for each tag in the dataset. The HR/PPM transmission capability was designed to lower the rate of transmission collisions when a large number (greater than 10 tags) were resident for long periods near a VEMCO hydrophone.

Table C-4
VEMCO Acoustic Tag Model and Specifications Used in the HOR Studies

Study Year	Model Number	Quantity Used	Diameter (mm)[1]	Length (mm)[1]	Mass Range (g)[2]	Used for sampling
2012	V5	961	5.0	12.0	0.62 to 0.71	Juvenile Chinook Salmon
2012	V6	1,435	6.0	16.5	1.01 to 1.08	Juvenile Steelhead

Notes: g = grams; HOR = Head of Old River; mm = millimeter.
Sources: [1] VEMCO 2012; [2] U.S. Fish and Wildlife Service 2012

All VEMCO hydrophones near the San Joaquin River–Old River divergence were deployed using bottom mounts fabricated from a section of railroad tie as an anchor. The hydrophones were installed using tensioned aircraft cable or rope lines extending to buoys on the surface (Figure 5-5 in Chapter 5, "Methods.").

C.2.2 ACOUSTIC TELEMETRY ASSESSMENT—VEMCO GEAR

The description of the methodologies will point primarily to publications of cooperative entities (i.e., the U.S. Fish and Wildlife Service, U.S. Bureau of Reclamation, and San Joaquin River Group Authority) in the south Delta research programs. These entities were responsible for the VEMCO gear's deployment, maintenance, and removal in 2011 (SJRGA 2013) and 2012 (discussed herein). Furthermore, these entities were responsible for the data downloads, processing, and transferal of these data to AECOM for analysis.

The VEMCO hydrophone/receiver network deployed in 2012 was similar to that in 2011 (J. Israel, pers. comm., 2013; SJRGA 2013). The locations of the hydrophones are shown in Table C-5. The HOR-W hydrophone defined the VEMCO Start Line used to determine O_E (Figure C-1). The SJLD.1 hydrophone defined the VEMCO-San Joaquin River-Finish Line used to determine O_E. The ORED.1 hydrophone defined the VEMCO-Old River-Finish Line used to determine O_E. VEMCO start and finish lines and the HTI start and finish lines may be viewed in Figure C-1. It should be noted that the VEMCO-SJR-Finish Line defined by hydrophone SJLD.1 is downriver from that SJR-Finish-Line used by VAMP in 2009 (defined in "Discussion," page 7-3).

Table C-5
UTM Coordinates Defining Entering and Exiting Positions and Transit Path for VEMCO-Derived Transit Speed Calculation

Hydrophone Station	UTM Coordinate	
	Easting	Northing
HORU	647893.49	4185567.59
HORD	647779.60	4185506.96
HOR-W	647368.00	4185705.00
HOR-E	647387.00	4185751.00
OREU.1	646538.88	4186218.57
OREU.2	646497.15	4186227.07
ORED.1	646528.08	4186286.86
SJLU.1	647772.77	4186159.86
SJLU.2	647662.99	4186143.09
SJLD.1	647771.19	4186172.21
SJLD.2	647771.67	4186130.53

Note: UTM = Universal Transverse Mercator
Sources: J. Israel, pers. Comm., 2013; Reclamation 2013; Turnpenny Horsfield Associates 2013

Juvenile salmonids implanted with VEMCO transmitters were grouped into samples for statistical analysis according to the sample creation methods described in Section 5.2.1. The calculation of O_E for VEMCO-derived data was the same as that for HTI-derived data, described in Section 5.2.2, "Calculation of Barrier Overall Efficiency and Overall Passage Efficiency."



Figure C-1 **2012 VEMCO Hydrophone Placements, VEMCO Start and Finish Lines, and HTI Start and Finish Lines near the Head of Old River Study Area**

C.3 RESULTS

C.3.1 OVERALL EFFICIENCY—CHINOOK SALMON COMPARED TO STEELHEAD

In 2012, the number of O_E samples ranged from 26 to 45 for juvenile Chinook salmon and steelhead (Table C-6). The O_E, the proportion of tags inserted into juvenile Chinook that passed the VEMCO SJR finish line (Figure C-1), was 94.0%.

Table C-6
Statistics for Overall Efficiency for Juvenile Salmonids Derived from VEMCO Data in 2012

Statistic	Chinook Salmon	Steelhead	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.940	0.974	-3.4	1.600	0.2059
Standard deviation	0.128	0.062	—	—	—
Minimum	0.500	0.667	—	—	—
Maximum	1.000	1.000	—	—	—
Samples (n)	26	45	—	—	—

Note: n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM 2013

For juvenile steelhead, O_E was 97.4%, which was 3.4 percentage points higher than for juvenile Chinook salmon, but the O_E was not significantly different between the two. As described for 2011 results (Section 6.1.6, subsection on "Overall Efficiency," in Chapter 6, "Results"), it is possible that fewer juvenile steelhead were eaten because they were larger (Table C-2) and better swimmers compared to the juvenile Chinook salmon.

C.3.2 2012 OVERALL EFFICIENCY—CHINOOK SALMON, HTI COMPARED TO VEMCO

The O_E derived from VEMCO tag detections of juvenile Chinook salmon was 32.2 percentage points higher than the O_E derived from HTI tag detections (Table C-7). However, it was hypothesized that this difference was attributable to the fact that most of the tagged juvenile Chinook salmon were eaten by predators before they passed the VEMCO SJR finish line (Figure C-1), but detected at the HTI SJR finish line were counted as passing down into the San Joaquin River. This was not the case with the HTI-derived estimate: Tags with a determined fate of predation before the HTI SJR finish line were removed from the numerator of the O_E calculation even if they were detected at the HTI SJR finish line.

The hypothesis that the higher value for VEMCO (32.2%) was attributable to the presence of eaten tags in the dataset was supported by comparing this difference to the mean of sample proportion eaten. The mean of HTI-derived sample proportion eaten was 38.2% (Section 6.2.1, "Proportion Eaten [Univariate Analyses]," in Chapter 6, "Results": Table 6-55), which is similar to the difference between VEMCO and HTI O_E.

Table C-7
Statistics for Overall Efficiency for Juvenile Chinook Salmon Derived from HTI and VEMCO Equipment in 2012

Statistic	HTI	VEMCO	Percentage Point Change	Kruskal-Wallis X^2	P-Value
Mean	0.618	0.940	-32.2	14.502	0.0001
Standard deviation	0.321	0.127	—	—	—
Minimum	0.000	0.500	—	—	—
Maximum	1.000	1.000	—	—	—
Samples (n)	27	26	—	—	—

Note: n = number of samples
Source: Data compiled by AECOM 2013

C.4 DISCUSSION

C.4.1 2012 CHINOOK SALMON COMPARED TO STEELHEAD (VEMCO-DERIVED DATA)

OVERALL EFFICIENCY

Of 460 VEMCO-tagged juvenile steelhead that arrived at the HOR study area, 16 were estimated to have been eaten during the cursory review performed by HTI (S. Johnston, pers. comm., 2013). This proportion eaten (3.5%), is probably underestimated given the higher HTI-derived proportion of steelhead eaten (24%) in 2011 (Table 6-54).

In 2012, juvenile steelhead O_E was 97.4%, which was 3.4% higher than that for juvenile Chinook salmon, but the O_E was not substantially different between the two (Table C-7). It seems highly likely that both steelhead and Chinook salmon O_E were overestimated in the VEMCO dataset because most of the eaten tags were not removed. This may be an avenue of future research, but this comparison should be done after the 6YSS team removes likely predation from the dataset.

C.4.2 2012 HTI-DERIVED DATA COMPARED TO VEMCO-DERIVED DATA

CHINOOK SALMON OVERALL EFFICIENCY

The juvenile Chinook salmon O_E derived from VEMCO tag detections was 32.2 percentage points higher than the O_E derived from HTI tag detections (94.0 % and 61.8%, respectively) (Table C-7). In Section C.3.2, "2012 Overall Efficiency—Chinook Salmon, HTI Compared to VEMCO," it was hypothesized that this difference resulted from most of the tagged juvenile Chinook salmon being eaten by predators not having been removed from the VEMCO-derived dataset.

Of 471 VEMCO tagged juvenile Chinook salmon and detected at the HOR study area, no tags were identified as having been eaten based on the cursory review provided by HTI in 2012–2013 (S. Johnston, pers. comm., 2013). The HTI-derived results estimated that sample proportion eaten was 38.2% of juvenile Chinook salmon in the HOR study area in 2012 (Table 6-55).

An unknown proportion (perhaps as much as 38.2%) of VEMCO tags in the 2012 dataset may have been eaten by predatory fishes and were not removed in the analysis reported here. Thus, positive bias existed in the O_E calculated from VEMCO-derived data, making a valid comparison of VEMCO tags to HTI tags impossible at this point. To make the data derived from these two sets of equipment directly comparable, additional study and development of criteria for identifying tags subject to predation are necessary.

C.5 RECOMMENDATIONS

After the 6YSS is completed, it is recommended that the predator classification methodology used by the 6YSS team be applied to the 2012 VEMCO data used in this evaluation of the HOR study area. Then, a valid comparison of O_E with the HTI-derived data from 2012 may be made to the 2012 VEMCO-derived and HTI-derived data. Further, after the tags have been determined to have been eaten can be removed from the VEMCO data with a greater degree of confidence, a comparison of protection efficiency (P_E) and proportion eaten derived from HTI data and from VEMCO data will be possible because these metrics rely heavily on predation determinations.

APPENDIX D

Transit Speed Analyses

D.1 INTRODUCTION

Transit speed was defined as the rate at which a tag passed through the hydrophone array. Transit speed was analyzed to determine whether it changed with different barrier treatments/years. In all years of study, the guidelines for determining the fate of a tag originally inserted into a juvenile salmonid provided a basis for comparing transit speed of those tags determined to have been eaten and those tags determined to have remained in juvenile salmonids through the Head of Old River (HOR) study area. Because looping behavior and movement against the current were pieces of evidence pointing toward a predation event, these tag behaviors were used to identify which tags had been eaten. Then transit speeds for tags that had been identified as having been eaten and not eaten were determined, and their mean transit speeds were examined. It was expected that mean transit speed through the HOR study area would be slower for tags determined to have been eaten than for tags determined not to have been eaten (Table D-1).

Table D-1
Objectives and Hypotheses Related to Transit Speed

Year	Objectives	Hypothesis Number	Hypotheses
2009–2012	Examine the juvenile Chinook salmon transit speed for each year of study as a basis for understanding barrier effectiveness and the influence of factors such as predation.	—	No hypothesis test possible.
2011	Examine juvenile steelhead transit speed for the only year these data were available, 2011, as a basis for understanding barrier effectiveness and the influence of factors such as predation.	—	No hypothesis test possible.
2011	Examine juvenile Chinook salmon and steelhead transit speed for the only year these data were available as a basis for understanding barrier effectiveness.	$HD1_0$	Transit speed for juvenile Chinook salmon was equal to transit speed for juvenile steelhead.
2012	Provide a comparison of transit speeds for juvenile Chinook salmon and steelhead determined using HTI and VEMCO gear.	$HD2_0$	For juvenile Chinook salmon and steelhead, VEMCO*-derived transit speed was equal to HTI**-derived transit speed.

Notes:
* = VEMCO (Bedford, Nova Scotia, Canada).
** = Hydroacoustic Technology, Inc. (Seattle, WA).
Source: Turnpenny Horsfield Associates and AECOM 2013

At the HOR study area from 2009 through 2012 barrier efficiency was the primary response metric of interest. However, analysis of the transit speed of each acoustically tagged juvenile salmonid provided information about behavior and water velocity that could be used to improve understanding of the behavioral responses to the barrier treatment at the HOR study area.

D.2 METHODS

D.2.1 TRANSIT SPEED CALCULATION—HTI EQUIPMENT

DETERMINATION OF START AND FINISH LINES

Start and finish line positions were derived from the furthest upstream and downstream hydrophone positions using all hydrophone positions from 2009 through 2012. A line perpendicular to the shoreline was drawn starting with these hydrophone positions. The Hydroacoustic Technology, Inc. (HTI; Seattle, Washington) San Joaquin River (SJR) start line (Figure C-1) used the position of Hydrophone (HD) 4 from the 2011 study. The HTI SJR finish line and the HTI Old River finish line were derived from the positions of HD 1 and HD 13, respectively, during the 2012 barrier study (Figures C-1 and D-1). Start and finish line Universal Transverse Mercator (UTM) coordinates are presented in Table D-2.

Table D-2
UTM Coordinates Defining Start and Finish Lines for HTI-Derived Transit Speed Calculations at the Head of Older River Study Area

	UTM Coordinate for End Position of Line			
	Right Bank (Easting)	Right Bank (Northing)	Left Bank (Easting)	Left Bank (Northing)
San Joaquin River start line	647379	4185796	647298	4185735
San Joaquin River finish line	647312	4185932	647284	4185974
Old River finish line	647081	4185864	647093	4185819

Notes: UTM = Universal Transverse Mercator
Right and left bank are determined by looking downstream
Source: S. Johnston, pers. comm., 2013

CALCULATION OF TRANSIT SPEED

A cross-product method was used to determine whether a tagged juvenile salmonid track position was on one side or the other of any given start/finish line. The cross-product value is negative on one side of the line, positive on the other, and 0 when exactly on the line. These values determined when a tagged juvenile salmonid track crossed the start and finish lines.

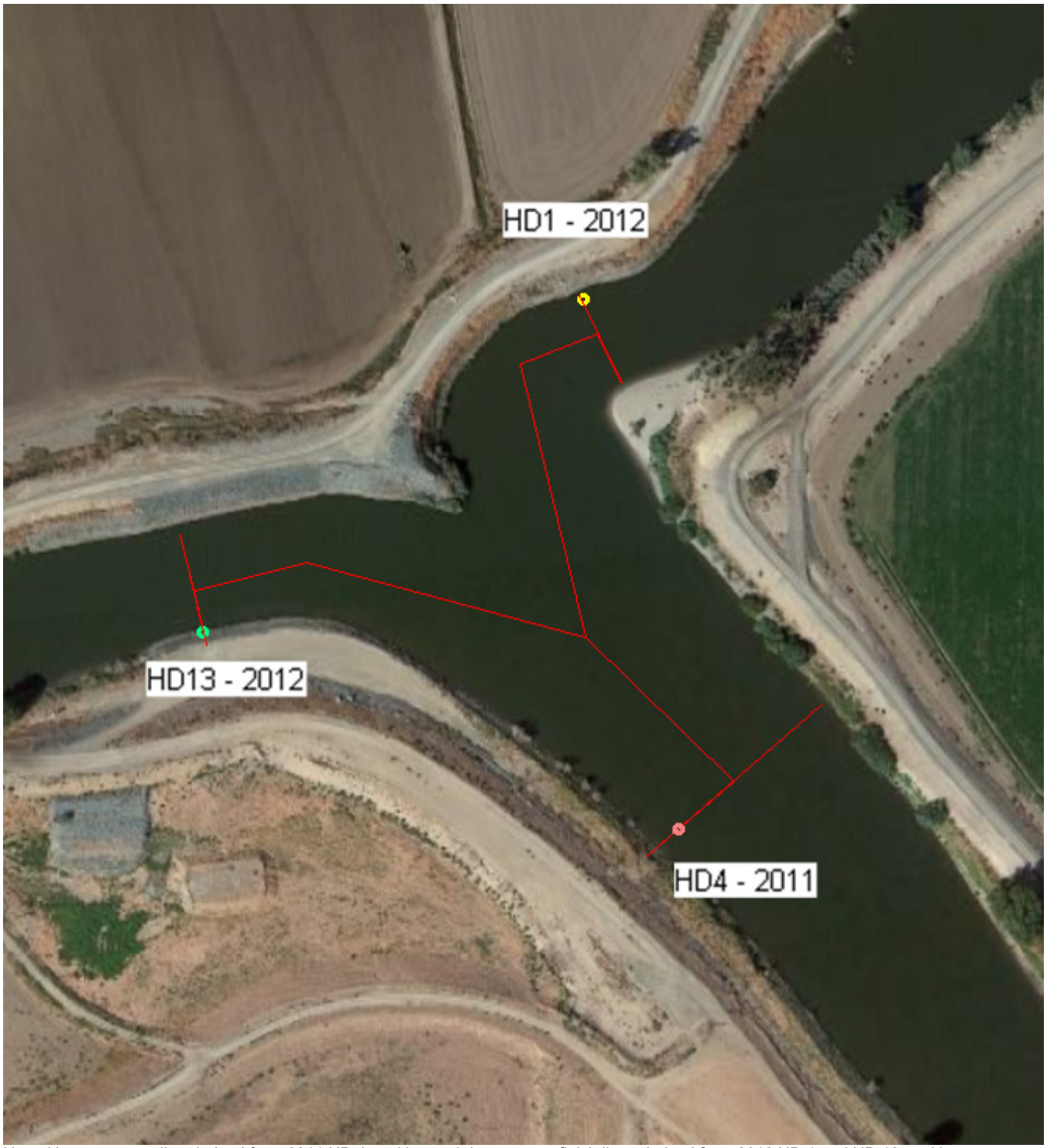
The following equation was used to determine whether a position is on one side of a line or another:

Test Value = (Bx – Ax) * (Cy – Ay) – (By – Ay) * (Cx – Ax)

Where:

Point A = Left bank of start or finish line, or (Ax,Ay)
Point B = Right bank of start or finish line, or (Bx,By)
Point C = Tag position test point, or (Cx,Cy)
Test Value = Positive on downstream side of line AB, negative on upstream side of line AB

Figure D-1 shows the HOR study area with start, finish, and path lines. Straight line segments were drawn between the start and finish lines, approximately mid-channel for each route. A standardized distance through the



Note: Upstream start line derived from 2011 HD 4 position and downstream finish lines derived from 2012 HD 1 and HD 13 positions.
Source: Hydroacoustic Technology, Inc.2013

Figure D-1 **Start and Finish Lines Used to Determine Transit Speed at the Head of Old River Study Area**

HOR study area array to be used for all fish in all years was calculated using these lines by adding all line segments for each route between the start and finish lines for each route. Thus, the standardized transit distance for the Old River route was 276.88 meters (m) and for the San Joaquin River route was 265.88 m.

To find the transit distance for "short" tracks (i.e. tracks that do not cross the start and/or finish lines), the point along the mid-channel line that is on the line perpendicular to the endpoint was found, and then the distance from that point to the next segment endpoint (perpendicular to the mid-channel line) was calculated. All segments traversed by the tagged juvenile salmonid were then summed to find the total distance made through the array area. This distance was then divided by the end time minus the start time for that fish to find transit speed in meters per second (m/s). To calculate a standardized "transit time," times were normalized by the proportion of the total transit distance that was actually travelled by each tagged juvenile salmonid.

The following equation was used to determine a point on a line segment perpendicular to the given point:

> Calculate the slope (m) and y-intercept (b) of the line segment from the center of the start line to the diversion point. These values were then used to find the point on the line segment that was perpendicular to tag position F:
>
> $Gx = [(m * Fy) + Fx – (m * b)] / (m^2 +1)$
> $Gy = m * Gx + b$
>
> Where:
>
> Point D = Start of first San Joaquin River line segment also center of HTI SJR start line, or (Dx,Dy)
> Point E = End of first San Joaquin River line segment at diversion point, or (Ex,Ey)
> Point F = Tag position to find perpendicular or first position inside start line, or (Fx,Fy)
> Point G = Point on segment DE perpendicular to point F, or (Gx,Gy)

An example of a tagged juvenile salmonid track from the HOR study area 2012 physical rock barrier study with the line segments overlaid is provided in Figure D-2.

D.2.2 TRANSIT SPEED CALCULATIONS—VEMCO EQUIPMENT

FATE DETERMINATION GUIDELINES

The fates of juvenile salmonids tracked with VEMCO (Bedford, Nova Scotia, Canada) equipment were determined based on a limited review by HTI. VEMCO tags that were determined during the analysis to be in predators or to be false positive detections were those that: (1) left the area of the HOR study area and returned days later; (2) made numerous, extremely quick movements between the San Joaquin and Old rivers; (3) made many crossings through culverts both downstream and upstream; or (4) made multiple upstream movements from downstream San Joaquin River hydrophones to upstream San Joaquin River hydrophones and/or Old River hydrophones. This coarse technique identified no juvenile Chinook salmon that were eaten out of the 961 tagged individuals released (0.0%) and 16 steelhead that were eaten out of the 1,435 tagged juvenile steelhead released (0.6% of total). In general, it is expected that the limited review left most of the eaten juvenile Chinook salmon and steelhead in the VEMCO dataset that was analyzed for barrier Operation Efficiency (O_E) and transit speed.



Note: Tagged fish number 2028.03 exits the array and continues down the San Joaquin River. Calculated transit speed for 2028.03 was 0.42 meter per second.

Source: Hydroacoustic Technology, Inc. 2013

Figure D-2 2012 HOR Study Area HTI Hydrophone Array with Start and Finish Lines Displayed

VEMCO Data Preparation for Transit Speed Calculation

Determination of Time Entering and Exiting the HOR Study Area

The time a tag (tagged juvenile salmonid) entered the HOR study area was determined to be the earliest time the tag was detected simultaneously at HOR-W (Head of Old River - West) and HOR-E (Head of Old River - East) (Figure C-1) (Table D-3). If a tag was never detected simultaneously at both of these receivers but was detected at only one receiver, the earliest detection time at that receiver was used.

Table D-3
UTM Coordinates Defining Entering and Exiting Positions and Transit Path for VEMCO-Derived Transit Speed Calculation

Hydrophone Station	UTM Coordinate	
	Easting	Northing
HORU	647893.49	4185567.59
HORD	647779.60	4185506.96
HOR-W	647368.00	4185705.00
HOR-E	647387.00	4185751.00
OREU.1	646538.88	4186218.57
OREU.2	646497.15	4186227.07
ORED.1	646528.08	4186286.86
SJLU.1	647772.77	4186159.86
SJLU.2	647662.99	4186143.09
SJLD.1	647771.19	4186172.21
SJLD.2	647771.67	4186130.53
Departure point	647269.00	4185823.00
San Joaquin P1	647239.00	4185932.00
Old River P1	647140.00	4185853.00
ORPt1	646825.00	4185804.00
ORPt2	646534.00	4186030.00
SJRPt1	647402.00	4186041.00
SJRPt2	647579.00	4186138.00

Note: UTM = Universal Transverse Mercator
Sources: J. Israel, pers. comm., 2013; Reclamation 2013; Turnpenny Horsfield Associates and AECOM 2013

The time a tag exited the HOR study area was determined to be the latest time the tag was detected simultaneously at the maximum number of VEMCO receivers at one of the downstream exit zones (San Joaquin River or Old River). For example, tagged juvenile Chinook salmon 1136865 was detected simultaneously at HOR-W and HOR-E at 20:10:17 on May 3, 2012. The tag then passed through the HOR study area and was detected downstream in the San Joaquin River. However, the tag was detected at only three of the downstream

hydrophones (SJLU.1, SJLU.2, and SJLD.1) simultaneously, at 20:47:16 on May 3, 2012. Therefore, tag 1136865 had a transit time of 0:36:59 hours.

Determination of Entering and Exiting Positions in the HOR Study Area

The "position on entering" for each tag was determined as follows:

1. If the tag was detected simultaneously at both upstream hydrophones, then "position on entering" was defined as the midpoint between the two hydrophones.

2. If the tag was detected only on one upstream hydrophone, then "position on entering" was defined as the mid-channel point on the cross-channel line perpendicular to the flow and passing through the hydrophone location.

The "position on exiting" for each tag was determined as follows:

1. If the tag was detected simultaneously at all four downstream hydrophones (either in San Joaquin River or Old River), then "position on exiting" was calculated to be the point equidistant from all four hydrophones.

2. If the tag was detected simultaneously at only three downstream hydrophones, then "position on exiting" was calculated to be the point equidistant from these three hydrophones.

3. If the tag was detected simultaneously at only two downstream hydrophones, then "position on exiting" was calculated to be the midpoint between these two hydrophones.

4. If the tag was detected at only one downstream hydrophone, then "position on exiting" was calculated to be the mid-channel point on the cross-channel line passing through this hydrophone.

Calculation of Transit Distance

The transit distance for each tag was then calculated as follows:

If the tag passed through the HOR study area and went to the Old River exit, then the transit distance was calculated as follows:

$$X_T = X_{ED} + X_{DO} + X_{OX}$$

Where:

X_T = transit distance
X_{ED} = distance from "position on entering" to divergence point
X_{DO} = distance from divergence point down Old River to ORPt2 (Table D-3), via Old River P1 and ORPt1
X_{OX} = distance from ORPt2 to "position on exiting"

If the tag passed through the HOR study area and went to the San Joaquin River exit, then the transit distance was calculated as follows:

$X_T = X_{ED} + X_{DS} + X_{SX}$

Where:

X_T = transit distance
X_{ED} = distance from "position on entering" to divergence point
X_{DS} = distance from divergence point down San Joaquin River to SJRPt2, via San Joaquin P1 and SJRPt1
X_{SX} = distance from SJRPt2 to "position on exiting"

Calculation of Transit Speed

For each tag that was detected with VEMCO gear both entering and exiting the HOR study area, it was possible to calculate a transit speed. After transit distance and transit time had been calculated, the transit distance was then divided by the exit time minus the entering time for that fish to find transit speed.

For example, tag 1136865 entered the HOR study area and was detected at both HOR-W and HOR-E. The tag passed through the study area and exited downstream in the San Joaquin River, detected at the SJLU.1, SJLU.2, and SJLD.1 hydrophones at the same time. So, the transit distance for this tag was calculated as follows:

X_T = 143.75 m + 510.97 m + 118.96 m = 773.68 m

Then the transit speed for tag 1136865 was 773.68 m/(0:36:59 hours) = 0.349 m/s

D.2.3 HYPOTHESIS TESTING

In Section D.2.1, "Transit Speed Calculation—HTI Equipment," and Section D.2.2, "Transit Speed Calculation—VEMCO Equipment," the estimation of an individual fish's transit speed is described. For each hypothesis tested, all transit speed observations for a given treatment were collected into a single population of observations, which was then compared statistically to the population of observations for the other treatment condition(s). Thus, population transit speed was used for hypothesis testing. This was possible because for transit speed, the sample unit was an individual fish. In contrast, O_E requires a number of individuals to calculate a proportion, and those individuals must all arrive (by definition of sample in Chapter 5, "Methods") during a period when there has been no significant change in barrier, light, or average channel velocity.

D.3 RESULTS

D.3.1 2009—JUVENILE CHINOOK SALMON TRANSIT SPEED

The mean population transit speed of all HTI tags that encountered the bio-acoustic fish fence (BAFF) in 2009 was 0.162 m/s. There was a difference in transit speed between tags in juvenile Chinook salmon that passed through the HOR study area when the BAFF was on versus when the BAFF was off (Table D-4). This result suggests that BAFF operations slowed down the migrating juvenile Chinook salmon compared to periods when the BAFF was off.

Table D-4 Statistics for Juvenile Chinook Salmon Population Transit Speed in 2009					
Statistic	**BAFF On (m/s)**	**BAFF Off (m/s)**	**Difference (m/s)**	**Kruskal-Wallis X^2**	**P-Value**
Mean	0.120	0.191	-0.071	16.808	<0.0001
Standard deviation	0.131	0.178	—	—	—
Minimum	0.001	0.001	—	—	—
Maximum	0.749	0.976	—	—	—

Notes: BAFF = bio-acoustic fish fence; m/s = meters per second
Sample size (n) is 161 with BAFF on and 244 with BAFF off
Source: Data compiled by Turnpenny Horsfield Associates and AECOM 2013

The mean population transit speed for juvenile Chinook salmon determined to have not been eaten was 0.162 m/s, whereas the mean population transit speed of eaten tags was 0.094 m/s (Table D-5). These results suggest that migrating juvenile salmonid may achieve a higher speed moving in a downstream direction (for example, see Figure 5-10) compared to predators. If these determinations of predation are largely correct, the predators in the HOR study area tended to remain resident for longer periods than juvenile Chinook salmonand moved more slowly as they searched for prey (for example, see Figure E-19).

Table D-5 Effect of Predation on Juvenile Chinook Salmon Population Transit Speed in 2009			
Statistic	**Not Eaten (m/s)**	**Eaten (m/s)**	**Difference (m/s)**
Mean	0.162	0.094	0.068
Standard deviation	0.164	0.110	
Minimum	0.001	0.000	
Maximum	0.976	0.613	

Notes: m/s = m per second
Sample size (n) is 410 for Not Eaten and 122 for Eaten
Source: Data compiled by Turnpenny Horsfield Associates 2013

D.3.2 2010—CHINOOK SALMON TRANSIT SPEED

The mean population transit speed of all HTI tags was 0.290 m/s. In contrast to 2009, there was no statistical difference between tags in juvenile Chinook salmon passing through the HOR study area when the BAFF was on versus when the BAFF was off (Table D-6). Thus, operation of the BAFF did not appear to slow down juvenile Chinook salmon in 2010.

Table D-6 Statistics for Chinook Salmon Population Transit Speed in 2010					
Statistic	BAFF On (m/s)	BAFF Off (m/s)	Difference (m/s)	Kruskal-Wallis X^2	P-Value
Mean	0.298	0.283	0.015	1.783	0.1818
Standard deviation	0.104	0.107			
Minimum	0.120	0.034			
Maximum	0.838	0.983			

Notes: BAFF = bio-acoustic fish fence; m/s = meters per second
Sample size (n) is 160 with BAFF on and 174 with BAFF off
Source: Data compiled by Turnpenny Horsfield Associates 2013

The mean population transit speed for juvenile Chinook salmon determined to not have been eaten was 0.290 m/s, and the mean population transit speed of eaten tags was 0.157 m/s (Table D-7). The 0.133 m/s change represents a 46% difference in speed between tags determined to have not been eaten and those determined to have been eaten. As in 2009, these results suggested that migrating juvenile salmonid tended to make purposeful speed moving in a downstream direction (Figure 5-10) compared to predators. As noted previously, for 2009, the predators that were tagged in the HOR study area commonly remained resident for longer periods and moved more slowly as they sought for prey (Figure E-19).

Table D-7 Effect of Predation on Juvenile Chinook Salmon Population Transit Speed in 2010			
Statistic	Not Eaten (m/s)	Eaten (m/s)	Difference (m/s)
Mean	0.290	0.157	0.133
Standard deviation	0.106	0.087	
Minimum	0.034	0.003	
Maximum	0.982	0.430	

Notes: m/s = meters per second
Sample size (n) is 334 for Not Eaten and 117 for Eaten
Source: Data compiled by Turnpenny Horsfield Associates 2013

D.3.3 2011—Juvenile Chinook Salmon and Steelhead Transit Speed

In 2011, the mean population transit speed for juvenile Chinook salmon was 0.068 m/s faster than for juvenile steelhead (Table D-8). Juvenile steelhead exhibited a broader range of transit speeds compared to juvenile Chinook salmon (Table D-8), especially on the lower end of the range. It appeared that some juvenile steelhead moved slowly compared to juvenile Chinook salmon (see "Minimum" row in Table D-8). These results supported the hypothesis that juvenile steelhead made more upstream movements, made more looping movements, and had more short holding periods in the study area than did juvenile Chinook salmon. All these types of movements would tend to reduce the overall juvenile steelhead population transit speed.

Table D-8
Statistics for Fish Determined to Have Not Been Eaten—Juvenile Chinook Salmon and Steelhead Population Transit Speed in 2011

Statistic	Chinook Salmon (m/s)	Steelhead (m/s)	Difference (m/s)	Kruskal-Wallis X^2	P-Value
Mean	0.535	0.467	0.068	54.425	<0.0001
Standard deviation	0.153	0.156			
Minimum	0.219	0.003			
Maximum	1.199	1.073			

Notes: m/s = meters per second
Sample size (n) is 966 for juvenile Chinook salmon and 395 for juvenile steelhead
Source: Data compiled by Turnpenny Horsfield Associates 2013

The mean population transit speed for juvenile Chinook salmon determined to have not been eaten was 0.535 m/s, and the mean population transit speed of eaten tags was 0.255 m/s (Table D-9). The 0.280 m/s change represents a 52% difference in speed between tags determined to have not been eaten and those determined to have been eaten.

Table D-9
Effect of Predation on Juvenile Chinook Salmon Population Transit Speed in 2011

Statistic	Not Eaten (m/s)	Eaten (m/s)	Difference (m/s)
Mean	0.535	0.255	0.280
Standard deviation	0.153	0.157	—
Minimum	0.219	0.002	—
Maximum	1.199	0.639	—

Notes: m/s = meters per second
Sample size (n) is 966 for Not Eaten and 109 for Eaten
Source: Data compiled by Turnpenny Horsfield Associates and AECOM 2013

The mean population transit speed for juvenile steelhead determined to have not been eaten was 0.467 m/s, and the mean population transit speed of tags determined to have been eaten was 0.160 m/s. The 0.307 m/s difference represents a 66% difference in speed between tags determined to have not been eaten and those determined to have been eaten (Table D-10). These results show that the higher population transit speeds of uneaten tags (i.e., juvenile salmonid) compared to eaten tags (i.e., predators) was consistent across both species studied. Because transit speeds were markedly higher for uneaten tags than for tags that were eaten for both juvenile Chinook salmon and steelhead, it may be useful to further develop transit speed as a component of criteria to identify predator-like behavior when conducting analysis of acoustic telemetry in future studies.

Table D-10 Effect of Predation on Juvenile Steelhead Population Transit Speed in 2011			
Statistic	**Not Eaten (m/s)**	**Eaten (m/s)**	**Difference (m/s)**
Mean	0.467	0.160	0.307
Standard deviation	0.156	0.125	
Minimum	0.003	0.001	
Maximum	1.073	0.544	

Notes: m/s = meters per second
Sample size (n) is 395 for Not Eaten and 125 for Eaten
Source: Data compiled by Turnpenny Horsfield Associates and AECOM 2013

D.3.4 2012—JUVENILE CHINOOK SALMON TRANSIT SPEED

In 2012, the mean population transit speed for juvenile Chinook salmon was 0.261 m/s (Table D-11). The 2012 treatment produced a transit speed that was slower than in 2011 (0.535 m/s: Table D-8) and in 2010 (0.290 m/s), but faster than in 2009 (0.162 m/s).

The mean population transit speed for juvenile Chinook salmon determined to have not been eaten was 0.261 m/s, and the mean population transit speed of eaten tags was 0.193 m/s. The 0.068 m/s difference represents a 26% difference in speed between tags determined to have not been eaten and those determined to have been eaten (Table D-12). These results suggest that migrating juvenile salmonid tended to make purposeful movement patterns in a downstream direction in every year studied compared to predators.

Table D-11 Statistics for Juvenile Chinook Salmon Population Transit Speed in 2012					
Treatment – Year	**Mean (m/s)**	**Standard Deviation (m/s)**	**Minimum (m/s)**	**Maximum (m/s)**	**Sample Size (n)**
Rock Barrier – 2012	0.261	0.163	0.001	0.667	119

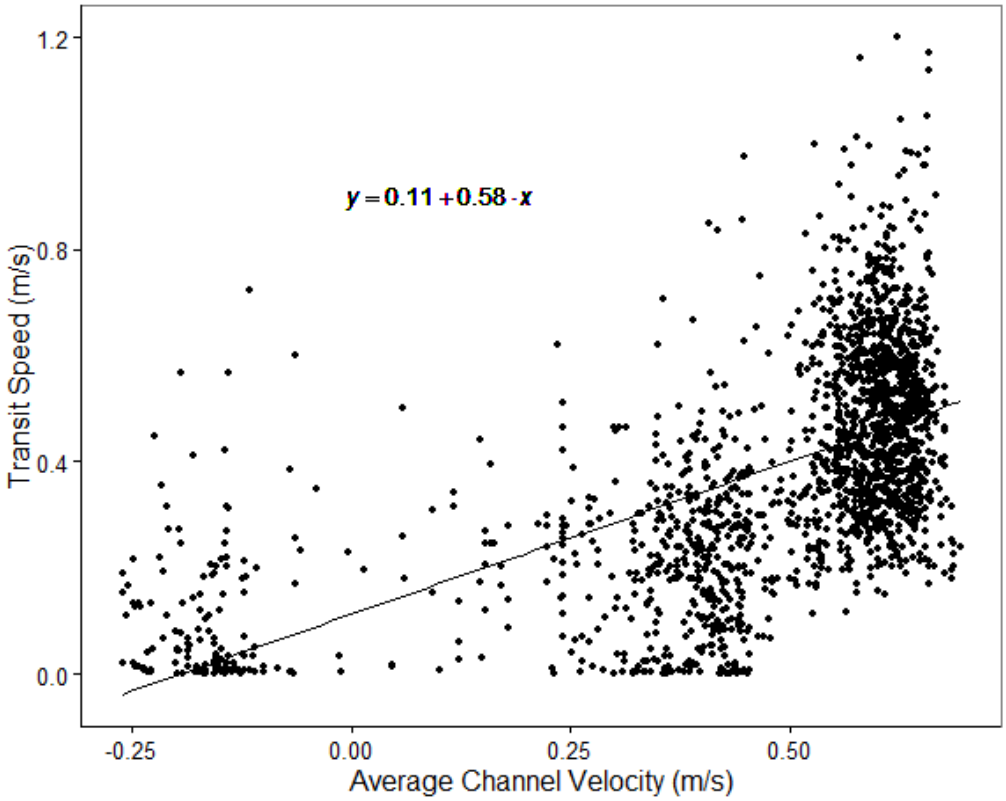
Note: m/s = meters per second; n = number of samples
Source: Data compiled by Turnpenny Horsfield Associates and AECOM 2013

Table D-12 Effect of Predation on Juvenile Chinook Salmon Population Transit Speed in 2012			
Statistic	**Not Eaten (m/s)**	**Eaten (m/s)**	**Difference (m/s)**
Mean	0.261	0.193	0.068
Standard deviation	0.163	0.156	
Minimum	0.001	0.001	
Maximum	0.667	0.657	

Notes: m/s = meters per second
Sample size (n) is 119 for Not Eaten and 74 for Eaten
Source: Data compiled by Turnpenny Horsfield Associates and AECOM 2013

D.3.5 TRANSIT SPEED—ALL YEARS COMPARED

For tags that were not eaten, there was a difference in mean transit speed of juvenile Chinook salmon among years (Kruskal-Wallis $X^2 = 1067.446$, $P < 0.0001$) (Table D-13). It seemed that at least one variable, average channel velocity (ACV) influenced mean transit speed: ACV was positively correlated with transit speed ($r = 0.583$, $P < 0.0001$) (Figure D-3). These results suggest that as the discharge increases and mean ACV increases, the mean transit speed increases, thereby supporting the hypothesis that juvenile Chinook salmon spent less time in the HOR study area at high discharges and ACVs. Those juvenile Chinook salmon that spent less time in the HOR study area may, in theory, have reduced the probability of encountering a predator. When 2010 and 2012 were grouped together statistically, they had a significantly faster transit speed than 2009. Transit speed was significantly higher in 2011 than in the other years, and 2011 showed the highest ACV observed among years. Statistical testing and grouping through pair-wise comparisons is described in Section 5.2.6 "STATISTICAL COMPARISONS." Note, however, that the Generalized Linear Model did not find substantial support for discharge as a predictor of predation probability (see Section 7.2, and Section 8.1.2, "Conduct Additional Analysis of Existing Data Using Supplementary Techniques").



Source: Turnpenny Horsfield Associates and AECOM 2013

Figure D-3 Average Channel Velocity Measured at the San Joaquin River at Lathrop Gauge and Juvenile Chinook Salmon Transit Speed Passing through the HOR Study Area Period (2009–2012)

Table D-13
Juvenile Chinook Salmon Transit Speed for Tags Determined to Have Not Been Eaten during Experimental Fish Release Periods

Treatment – Year	Discharge Minimum (cfs)	Discharge Maximum (cfs)	Mean ACV (m/s) (SD)	Mean Transit Speed (m/s) (SD) Tags Not Eaten	Statistical Grouping of Transit Speed
BAFF – 2009	-1,300	2,070	0.186 (0.269)	0.162 (0.164)	a
BAFF – 2010	913	3660	0.510 (0.131)	0.290 (0.106)	b
No barrier – 2011	4,250	8,040	0.605 (0.034)	0.535 (0.153)	c
Rock barrier – 2012	210	2,620	0.371 (0.076)	0.261 (0.163)	b

Notes: ACV = average channel velocity; BAFF = bio-acoustic fish fence; cfs = cubic feet per second; m/s = meters per second; SD = standard deviation
Source: Data compiled by Turnpenny Horsfield Associates 2013

D.3.6 2012—HTI- AND VEMCO-DERIVED TRANSIT SPEED

In 2012, the difference in the mean juvenile Chinook salmon population transit speed derived from VEMCO data when compared to HTI data was 0.037 m/s, and this difference was significant (Table D-14). This result was unexpected, because it was hypothesized that VEMCO-derived data contained a number of tags that had been eaten but were not removed. Given the faster transit speeds for uneaten tags (Tables D-5, D-7, D-9, and D-12), it was expected that VEMCO-derived samples would have contained several tags with slower transit speeds. There may be a need to revisit the VEMCO data set in light of these initial findings.

Table D-14
Statistics for Juvenile Chinook Salmon Population Transit Speed in 2012

Statistic	HTI (m/s)	VEMCO (m/s)	Difference (m/s)	Kruskal-Wallis X^2	P-Value
Mean	0.261	0.298	-0.037	4.749	0.0293
Standard deviation	0.163	0.176			
Minimum	0.001	0.003			
Maximum	0.667	0.880			

Notes: m/s = meters per second
Sample size (n) is 119 for HTI and 456 for VEMCO
Source: Data compiled by Turnpenny Horsfield Associates 2013

D.4 DISCUSSION

D.4.1 TRANSIT SPEED: BAFF ON COMPARED TO BAFF OFF

In 2009, transit speed with the BAFF on was substantially slower than with the BAFF off (Table D-4). In 2010, there was very little difference in juvenile Chinook salmon transit rates when the BAFF was on or off. In addition, the 2010 BAFF on transit speed was greater than the 2009 BAFF on transit speed (Kruskal-Wallis $X^2 = 154.124$, P-value < 0.0001). These results were consistent with the hypothesis that discharge determines ACV and, in turn, that ACV influences transit speed. This hypothesis also was supported by the transit speed comparison between

years: The highest discharge magnitudes (Figure 3-1) produced the highest mean transit speed (Table D-13); the intermediate discharge magnitude years produced intermediate transit speeds; and the lowest discharge magnitude year, 2009 (Figure 3-2), produced the lowest mean transit speed (Table D-13). For all years combined, an important linear relationship exists between transit speed and ACV (Figure D-3).

D.4.2 POPULATION TRANSIT SPEED: NOT EATEN COMPARED TO EATEN

The population transit speed for 2011 juvenile Chinook salmon that were not eaten (0.535 m/s) (Table D-8) was noted to be the highest observed during the 4 years of the study (Tables D-13). This is partially because of the relationship between discharge and transit speed, as described in the previous section. These results suggest that if individual transit speed is used as an indicator of predation probability, then it should be the difference between the mean transit speed for that year and that individual's transit speed that is considered when accounting for interannual differences in ACV and discharge.

In contrast to the high juvenile Chinook salmon transit rate in 2011, the low transit rate in 2009 appeared to be related to: (1) lower discharges and negative flows that led to lower ACV; (2) the smaller size of juvenile Chinook salmon individuals used in 2009 compared to other years (Table 5-1); and (3) the higher tag burden that the 2009 fish carried compared to the lower tag burden carried by fish in the other years (Table 5-3). All of these factors may interact to reduce transit speed. Additionally, low discharge, low ACV, and low transit speed could possibly interact to influence proportion eaten because slower transit speed could, at least theoretically, increase the probability of predator-prey encounters. However, size (fork length) of the juvenile was not found to be a well-supported predictor of predation probability from generalized linear modeling; other discharge-related factors (such as turbidity) also may play a role, and they are discussed further in Section 8.1.2, "Conduct Additional Analysis of Existing Data Using Supplementary Techniques."

In 2011, juvenile steelhead which were determined to have been uneaten also traveled through the HOR study area at a higher rate than tags determined to have been eaten (i.e., predators) (Table D-10). Transit rates for uneaten steelhead were slower than for uneaten juvenile Chinook salmon (Table D-8), probably because of the short holding periods, upstream movements, and looping behavior sometimes seen in steelhead.

D.4.3 2012—TRANSIT SPEED, HTI- COMPARED TO VEMCO-DERIVED DATA

The mean juvenile Chinook salmon transit speed for HTI tags passing through the HOR study area in 2012 was 0.261 m/s (Table D-14). The mean transit speed of juvenile Chinook salmon derived from VEMCO data, 0.298 m/s, was 0.037 m/s faster than the mean transit speed of juvenile Chinook salmon derived from HTI data.

This result was unexpected because the study hypothesized that the VEMCO-derived data contained a number of tags that were eaten but were not removed. Because of the slower transit speeds for eaten tags (Tables D-5, D-7, D-9, and D-12), the logical expectation was that VEMCO-derived observations should have contained several tags with slower transit speeds and should have produced slower transit speeds compared with HTI-derived data.

It was hypothesized that the difference in distance to the SJR finish lines, 554 m between the HTI and VEMCO SJR finish lines, may have caused this. The HTI SJR finish line was just downstream from the scour hole. Thus, juvenile salmonids that passed into the scour hole may have been slowed by the lower velocities that were often observed in that area (Figure 3-17). The VEMCO-tagged juvenile salmonids perhaps were slowed by the scour

hole, but after they were out of the scour hole, they may have accelerated to a speed closer to the ACV (measured at San Joaquin River at Lathrop gauge). Another explanation is that the two methods routinely predict different transit speeds. This last possibility suggests that further study is needed.

D.5 RECOMMENDATIONS

Transit speed was identified as a quantitative attribute that can assist in classifying predation on juvenile salmonids. It is recommended that this attribute be used to aid predation classification in future studies. Tagged juvenile salmonids that were classified as having been preyed upon passed through the HOR study area at a slower rate than tagged juvenile salmonids that were not eaten.

It is further recommended that the use of transit speed as one criterion for classifying predation also take into account the relationship between discharge, ACV, and transit speed. Individual transit speed should be evaluated as an indicator of predation probability. The individual transit speed should be compared to the mean transit speed for all tags experiencing the same conditions in a specific year. However, because the behavior of juvenile steelhead can mimic the behavior of predators, it is recommended that transit speed evaluation be species-specific.

The fact that the VEMCO-derived transit speed was routinely faster than the HTI-derived estimate of transit speeds is important. It may be that the difference in distance between the finish lines between the two methods may have caused this difference. It is possible, however, that these two methods produced systematically different estimates of transit speed. Further work should be undertaken to determine whether these methods are producing systematically different results.

APPENDIX E

Fish Fate Determination Guidelines

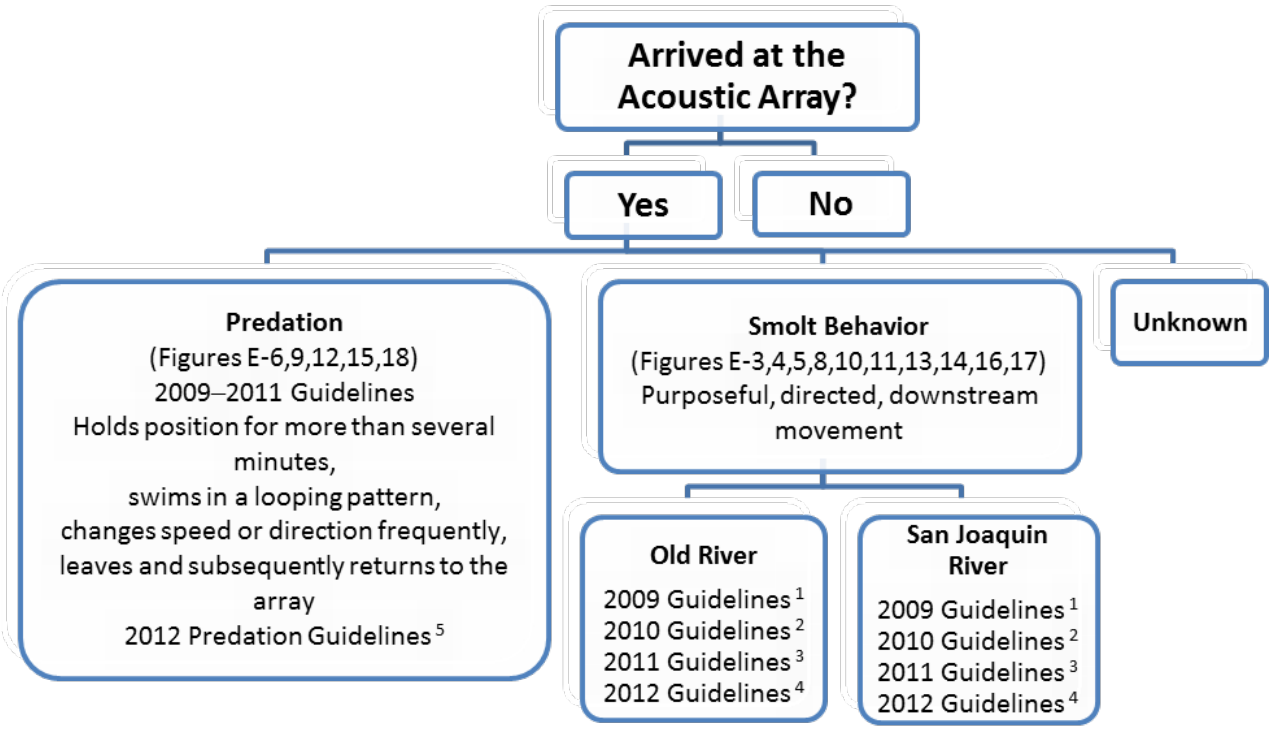
E FATE DETERMINATION GUIDELINES

During each of the Head of Old River (HOR) study years (2009 through 2012), a set of fish fate determination guidelines was applied to the observed juvenile salmonid tracks recorded at the HOR study area to classify whether the individual exhibited behaviors consistent with passing a juvenile salmonid or predatory fish species. In addition, standardized sets of rules were used to determine whether tagged fish exited the study area via Old River or the San Joaquin River. These fate classifications were necessary to test individual study hypotheses in the presence or absence of different barrier types. In 2009 and 2010, a non-physical barrier (referred to as BAFF throughout the report) was installed at the HOR study area and was evaluated. In 2011, no barrier was in place because of high river flows. However, deterrence fates were still determined for the 2011 data set, referenced to the position of the non-physical barrier installed in 2010. A physical barrier (referred to as rock barrier throughout the report) was installed at the HOR study area in 2012. A summary of the specific fate determination metrics developed during each study year is as follows:

(1) 2009–2012: Predation, juvenile salmonid behavior, or unknown (Figure E-1).

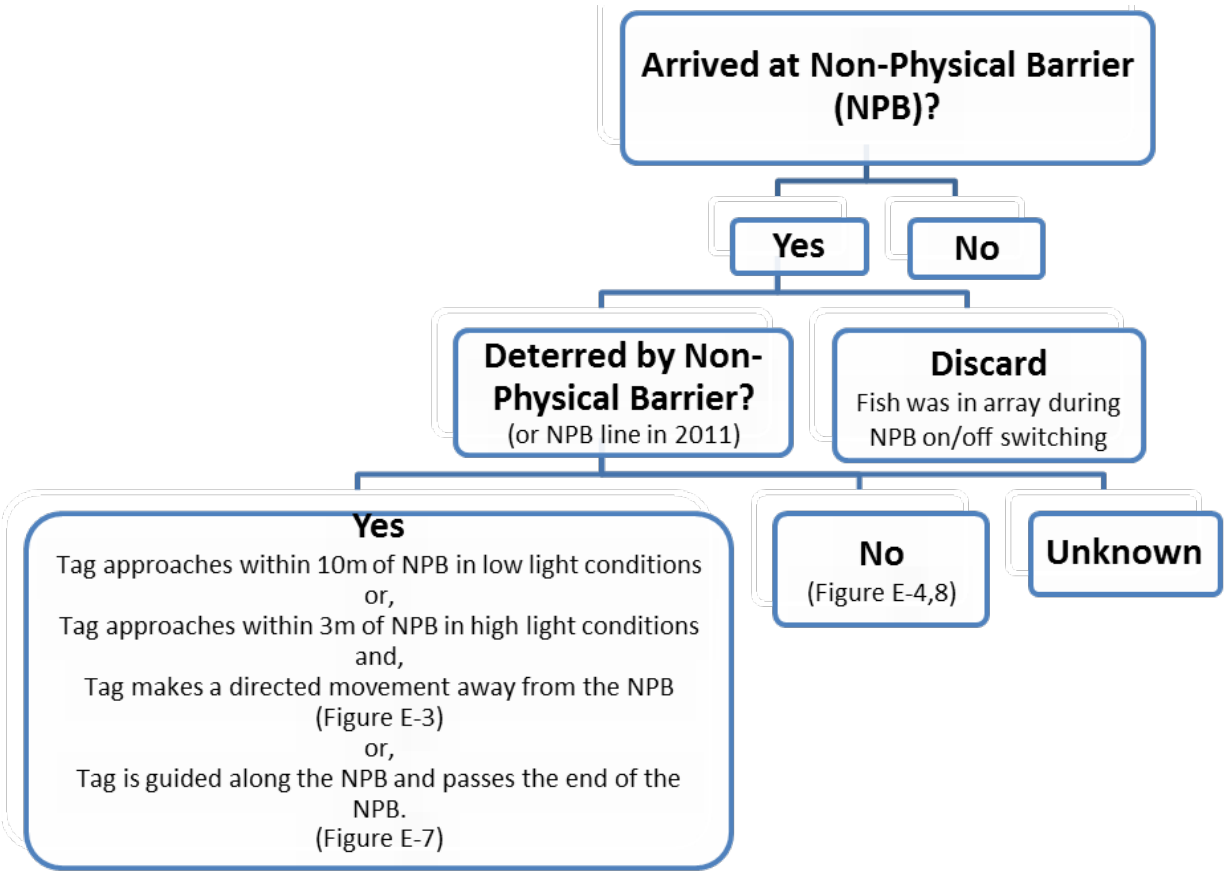
(2) 2009–2011: Deterred/undeterred by the non-physical barrier (or referenced to the 2010 non-physical barrier line for the 2011 no-barrier study), or unknown (Figure E-2). Fish deterrence fates were not determined for the 2012 physical barrier installation.

(3) 2009–2012: Final fate—Old River, San Joaquin River, predation, or unknown (Figure E-1).



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-1 **Flow Chart of Fish Fates Classification Categories Used to Establish Presumed Predation and Exit Route Selection for the HOR Study Area 2009–2012 Analyses**



Note: NPB = non-physical barrier

Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-2 **Flow Chart of Data Analysis for Determining Whether a Tag Was Deterred by the Non-physical Barrier (or Non-physical Barrier Line) for the HOR Study Area 2009–2010 Analyses**

E.1 2009 FATE DETERMINATION GUIDELINES

E.1.1 DETERMINING DETERRENCE OF A JUVENILE CHINOOK SALMON

(1) Learn what you can about the hydraulics at the site during the time of the individual's approach to the non-physical barrier (NPB): what is the discharge, Q (cubic feet per second [cfs]) at the San Joaquin River at Lathrop (SJL) gauge, and what is the average channel velocity (ACV)?

(2) Evaluate the tag for predator behavior (see "Determining Predation of a Juvenile Chinook Salmon," below) before evaluating for deterrence. If a juvenile Chinook salmon has been eaten before approach to the NPB, it cannot be deterred. A juvenile Chinook salmon is deterred if (a) it approaches within 10 meters (m) of the NPB under low-light conditions or within 3 m of the NPB during high-light conditions, (b) it makes some directed movement away from the NPB, or (c) it is guided along the NPB line and passed the end of the NPB.

E.1.2 DETERMINING PREDATION OF A JUVENILE CHINOOK SALMON

(1) Be aware of all the information acquired under "Determining Deterrence of a Juvenile Chinook Salmon," listed previously.

(2) Evaluate the two-dimensional (2D) track for juvenile Chinook salmon behavior. Juvenile Chinook salmon behavior is evident by purposeful, directed movement downstream, even if that directed movement is found only in the first portion of a 2D track. At the HOR study area in the scour hole, fish may follow a semicircular path because of an eddy current. This does not necessarily mean the tagged juvenile salmonid has been eaten by a predator.

(3) Evaluate the 2D track for predator behavior. The following behaviors were observed in predators at the HOR study area using dual-frequency identification sonar (DIDSON):

   (a) Predator behavior was evident when the tagged juvenile held position for time periods over several minutes, swam in loops in the area, swam upstream repeatedly, or changed speed or direction often.
   (b) A single 90-degree turn was not definitive proof that a tagged juvenile salmonid was in a predator.
   (c) If a tag left the hydrophone array and then came back into the array, it was assigned the fate of "predation."
   (d) If a track stopped in the center of the array or was otherwise incomplete, it sometimes was necessary to go back to the original raw acoustic tag file (.RAT file) using MarkTags (Hydroacoustic Technology, Inc., Seattle, Washington) to add additional data to get both longer tracks and longer trailing ends of tag detections. If a new database was to be created, the correct database was loaded into AcousticTag (Hydroacoustic Technology, Inc., Seattle, Washington) before creating the database.
   (e) In a track, 2D positions that were outside of the array had lower precision than those inside the array, and were not used solely to determine fate.

(4) If it was unclear which category a track belonged to using the above criteria, it was assigned the fate of "Unknown."

(5) Use weight of evidence of the data tracks to make the determination of the fate of predation or not.

E.1.3 DETERMINING THE FATE OF A JUVENILE CHINOOK SALMON IN 2009

(1) Be aware of all the information acquired under "Determining Deterrence of a Juvenile Chinook Salmon" and "Determining Predation of a Juvenile Chinook Salmon" listed previously.

(2) Evaluate the 2D track for juvenile Chinook salmon and predator behaviors. If the track is found to have not been eaten, then continue.

(3) Use the individual hydrophone display to find which hydrophone detected the tag last.

For NPB on: If the tag is last detected on hydrophone (HD) 1 (pink) and the signal slowly diminishes, indicating that the tag is steadily moving away from that hydrophone, then the fate of the San Joaquin River is assigned.

If the tag is last detected on HD 1 (pink), the signal strength is high, and the signal terminates quickly, indicating passage behind the divergence peninsula, then the fate of the Old River is assigned.

For NPB off: If the tag is last detected on HD 1 (pink) and the signal slowly diminishes, indicating that the tag is steadily moving away from that hydrophone, then the fate of the San Joaquin River is assigned.

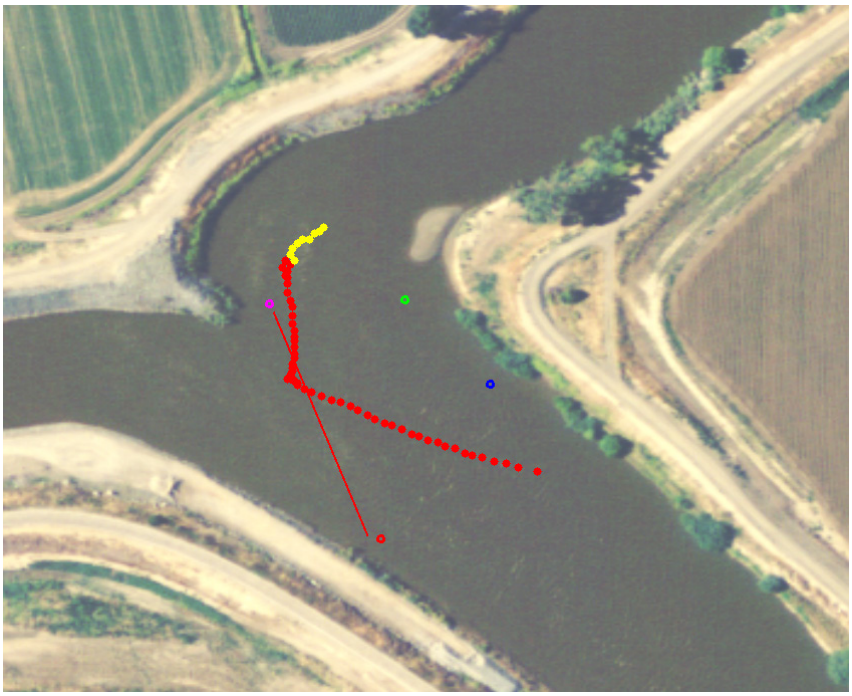
If the tag is last detected on HD 2 (green) or HD 3 (blue) and the signal slowly diminishes, or if the tag is last detected on HD 1 (pink), the signal strength is high, and the signal terminates quickly, indicating passage behind the divergence peninsula, then the fate of Old River is assigned.

(4) When using the foregoing rules, if it is not clear which category a track belongs, then the fate of "Unknown" is assigned.

(5) Use the preponderance of evidence to make the determination of predation or not.

E.2 2009 TAGGED JUVENILE CHINOOK SALMON FATE EXAMPLES

Examples of individual tagged juvenile Chinook salmon tracks from study year 2009 categorized as alive not eaten by a predator with fates of deterred, undeterred, and did not encounter the barrier are shown in Figures E-3, E-4, and E-5, respectively. Figure E-6 shows the track of a tagged juvenile Chinook salmon categorized as having been eaten by a predator. In all figures, the yellow dots at the end of each track represent the last 10 individual positions of the tagged juvenile Chinook salmon for that track.



Note: the bubble curtain was often swept downstream a few meters near the water surface, causing deterrence events to appear downstream of the BAFF line

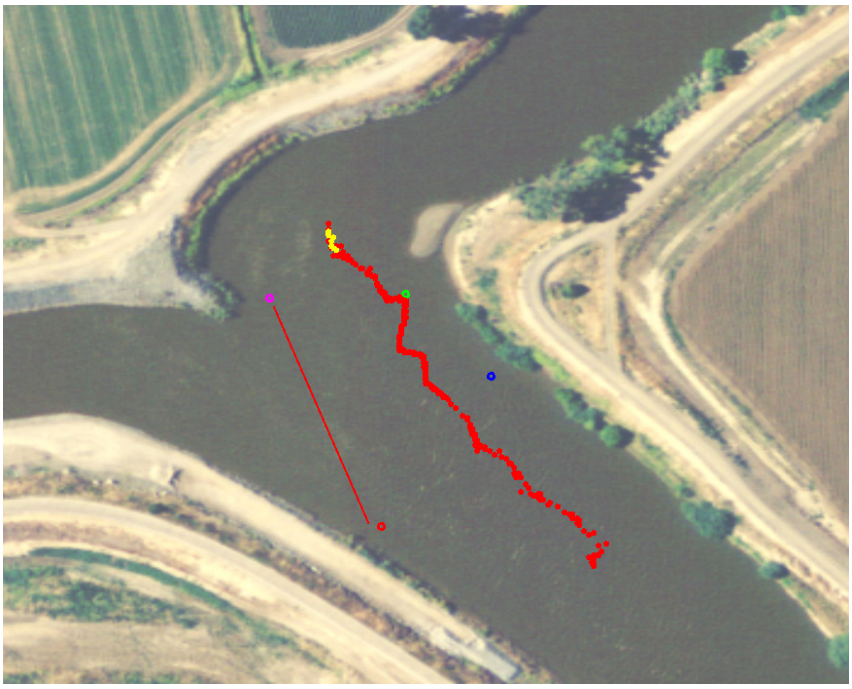
Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-3 **Tagged Juvenile Chinook Salmon Number 6214.15 Deterred by the BAFF (BAFF Operating) at 12:07 PDT on April 24, 2009, and Exiting the Array Down the San Joaquin River at the HOR Study Area**



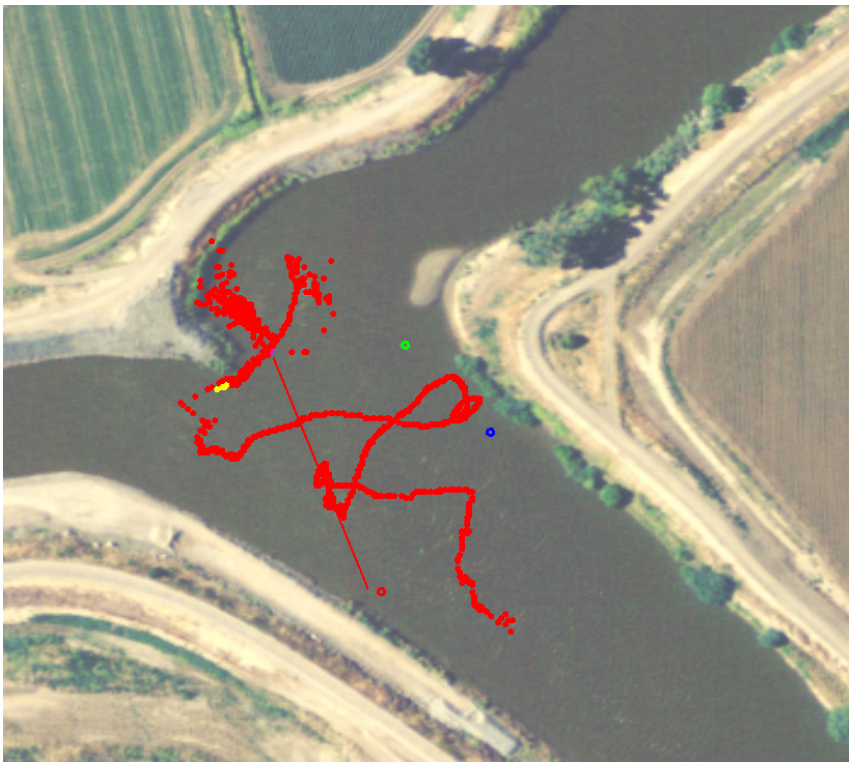
Note: The 2D trace ends at the BAFF because hydrophones 2, 3, and 4 cannot detect tag transmissions through the bubble curtain.
Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-4 **Tagged Juvenile Chinook Salmon Number 6514.21 Passes through the BAFF (BAFF Operating) at 0:37 PDT on May 15, 2009 and Exits Array down the Old River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-5 **Tagged Juvenile Chinook Salmon Number 6828.11, Designated as Having Never Experienced the BAFF (Did Not Approach Within 10 meters) at 19:03 PDT on May 2, 2009, Exits Array Down the San Joaquin River**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-6 **Tagged Juvenile Chinook Salmon Number 6310.11, Designated as Having Been Eaten by a Predator, was Present in the Array Between 06:19 and 07:46 PDT, May 2, 2009, and Exited Down the Old River (Yellow Dots)**

E.3 2010 FATE DETERMINATION GUIDELINES

(1) Be aware of all the information acquired under "Determining Deterrence of a Juvenile Chinook Salmon" and "Determining Predation of a Juvenile Chinook Salmon" noted previously.

(2) Evaluate the 2D track for tagged juvenile Chinook salmon and predator behaviors. If the track is found to have not been eaten, then continue.

(3) Use the individual hydrophone display to find which hydrophone detected the tag last and whether the detection's signal strength slowly diminishes on that hydrophone, indicating that it was moving steadily away from that hydrophone.

If the tag is last detected on HD 1 (pink) or HD 8 (peach) and the signal slowly diminishes, then the fate of the San Joaquin River is assigned.

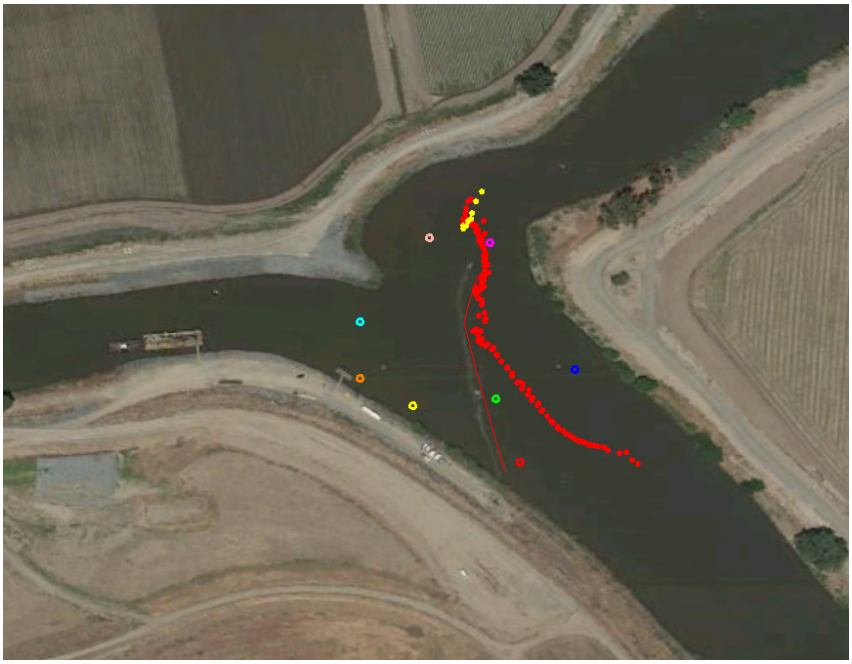
If the tag is last detected on HD 7 (light blue) and the signal slowly diminishes, then the fate of the Old River is assigned.

(4) When using the foregoing rules, if it is not clear in which category a track belongs, "Unknown" is assigned.

(5) Use the weight of evidence to make the determination of predation or not.

E.4 2010 TAGGED JUVENILE CHINOOK SALMON FATE EXAMPLES

Examples of individual tagged juvenile chinook salmon tracks from study year 2010 categorized as not eaten by a predator with fates of deterred and undeterred are shown in Figures E-7 and E-8, respectively. Figure E-9 shows the track of a tagged juvenile Chinook salmon categorized as having been eaten by a predator. In all figures, the yellow dots at the end of each track represent the last 10 individual positions of the tagged fish for that track.



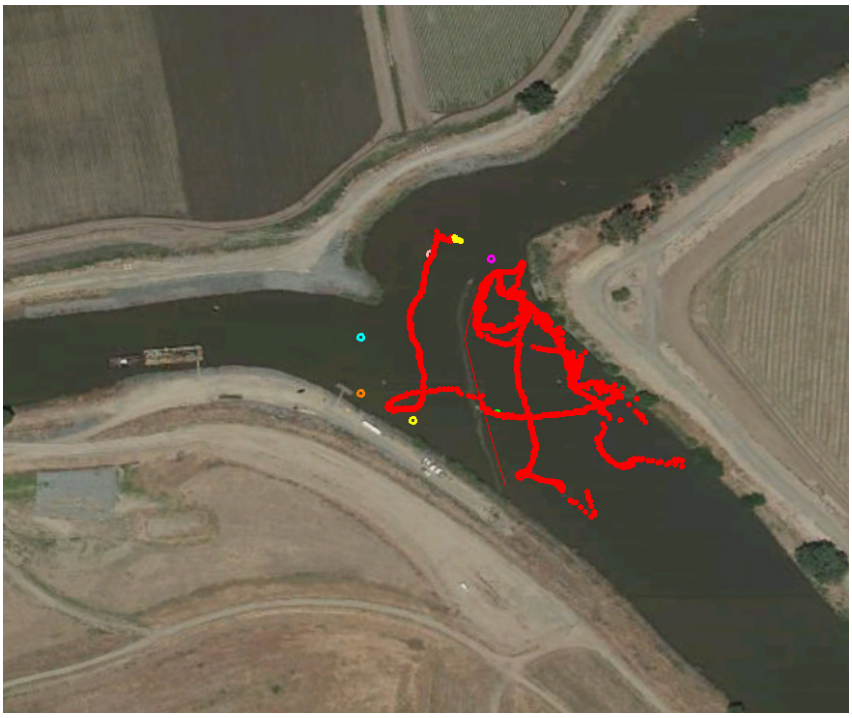
Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-7 **Tagged Juvenile Chinook Salmon Number 5441.12 Deterred by the BAFF (BAFF Operating) at 13:00 PDT on May 19, 2010, and Exiting the Array Down the San Joaquin River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-8 **Tagged Juvenile Chinook Salmon Number 5437.14 Passing through the BAFF (BAFF Operating) at 0:27 PDT on April 28, 2010, and Exiting the Array Down the Old River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-9 **Tagged Juvenile Chinook Salmon Number 5680.02 Designated as Having Been Eaten by a Predator was Present in the Array Between 6:53 and 9:21 PDT on May 8, 2010, and Exited the Array Down the San Joaquin River at the HOR Study Area**

E.5 2011 FATE DETERMINATION GUIDELINES

(1) Be aware of all the information acquired under "Determining Deterrence of a Juvenile Chinook Salmon" and "Determining Predation of a Juvenile Chinook Salmon" noted previously.

(2) Evaluate the 2D track for tagged juvenile Chinook salmon and predator behaviors. If the track is found to have not been eaten, then continue.

(3) Use the individual hydrophone display to find which hydrophone detected the tag last and whether the detection's signal strength slowly diminishes on that hydrophone, indicating that it was moving steadily away from that hydrophone.

If the tag is last detected on HD 5 (light blue) or HD 9 (orange) and the signal slowly diminishes, then the fate of the Old River is assigned.

If the tag is last detected on HD 1 (yellow), HD 6 (peach), HD 7 (teal), or HD 8 (pink), and the signal slowly diminishes, then the fate of the San Joaquin River is assigned.

(4) When using the foregoing rules, if it is unclear in which category a track belongs, "Unknown" is assigned.

(5) Use the weight of evidence to make the determination of predation or not.

E.6 2011 TAGGED JUVENILE CHINOOK SALMON AND STEELHEAD FATE EXAMPLES

Examples of individual tagged juvenile Chinook salmon tracks from study year 2011 categorized as alive not eaten by a predator which took routes of the San Joaquin and Old rivers are shown in Figures E-10 and E-11, respectively. Figure E-12 shows the track of a tagged juvenile Chinook salmon categorized as having been eaten by a predator. In all figures, the yellow dots at the end of each track represent the last 10 individual positions of the tagged fish for that track.

Examples of individual tagged juvenile steelhead tracks from study year 2011 categorized as alive not eaten by a predator which took routes of San Joaquin and Old rivers are shown in Figures E-13 and E-14, respectively. Figure E-15 shows the track of a tagged juvenile steelhead categorized as having been eaten by a predator. In all figures, the yellow dots at the end of each track represent the last 10 individual positions of the tagged juvenile steelhead for that track.



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-10 **Tagged Juvenile Chinook Salmon Number 5007.31 Passing through the Array at 16:51 PDT on May 18, 2011 and Exiting Down the San Joaquin River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-11 **Tagged Juvenile Chinook Salmon Number 5113.16 Passing through the Array at 12:59 PDT on June 18, 2011 and Exiting Down the Old River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-12 **Tagged Juvenile Chinook Salmon Number 5506.13 Designated as Having Been Eaten by a Predator was Present in the Array Between 1:43 and 20:38 PDT on June 10, 2011, and Exited the Array Down the San Joaquin River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-13 **Tagged Juvenile Steelhead Number 6354.04 Passing through the Array at 00:41 PDT on May 7, 2011 and Exiting Down the San Joaquin River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-14 **Tagged Juvenile Steelhead Number 5059.04 Passing through the Array at 03:27 PDT on May 7, 2011 and Exiting Down the Old River at the HOR Study Area**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-15 **Tagged Juvenile Steelhead Number 8965.04 Designated as Having Been Eaten by a Predator was Present in the Array Between 03:12 and 15:51 PDT on May 26, 2011, and Exited the Array Down the San Joaquin River at the HOR Study Area**

E.7 2012 FATE DETERMINATION GUIDELINES

(1) Be aware of all the information acquired under 2012 Predation Guidelines.

(2) Evaluate the 2D track for tagged juvenile Chinook salmon and predator behaviors. If the track is found to have not been eaten, then continue.

If the tag is detected in the array of hydrophones located downstream from the physical barrier in Old River, then the fate of the Old River is assigned.

If the tag is last detected on HD 1 (yellow), HD 2 (green), or HD 3 (blue) and the signal slowly diminishes, indicating that the tagged fish is steadily moving away from that hydrophone, then the fate of the San Joaquin River is assigned.

(3) When using the foregoing rules, if it is unclear which category a track belongs, "Unknown" is assigned.

(4) Use the weight of evidence to make the determination of predation or not.

E.8 2012 PREDATION GUIDELINES

In 2012 at the HOR study area, tracks of juvenile salmonids were evaluated to determine the fate of each tagged fish. In addition to determining which route the fish took (either the Old River or the San Joaquin River), the tracks were examined and a determination was made regarding whether or not the track exhibited predator-like behavior, indicating that a predator had eaten the tagged juvenile salmonid.

In past years (2009, 2010, and 2011), rules were developed for determining whether a particular track appearance would lead to that tagged juvenile salmonid being classified as having been eaten by a predator. Flow data were not available for the periods of study during these years. Because of the presence of the physical rock barrier in 2012, the flow patterns at the HOR study area were expected to be very different than in previous years, possibly leading to differences in tagged juvenile salmonid tracks selection. This proved to be the case, and many more juveniles exhibited one or more loops in their tracks than had been seen in previous years.

During the initial fate determinations, many of these juvenile salmonid tracks (73) were temporarily classified as "Unknown" for the category "Predation1." In 2012, acoustic Doppler current profiler (ADCP) data were collected at the HOR study area, allowing flow fields to be measured and a 5-m flow vector grid to be developed for 15-minute intervals during much of the study period. These data then were imported into EonFusion (Hobart, Tasmania, Australia) to visually show the magnitude (by varying color) and direction (by arrow direction) of flow on a geo-referenced image of the HOR study area, matched in time to the tagged juvenile salmonid track data.

A track reevaluation process was then performed for those 73 unknown tagged juvenile salmonid tracks to determine whether the loops or other potentially predator-like behavior was caused by the special flow conditions recorded by the ADCP created by the physical barrier in 2012.

The rules used in making predation determinations included the criteria developed for previous years, as well as the following additions:

(1) The rule about a closed loop being definitive of a predator was removed.

(2) A new looping rule was made, stating that loops are not definitive of predator behavior. The fate determination should be dependent on discharge; looping behavior that goes against medium to heavy flows suggests predator behavior.

(3) Upstream movement behavior was no longer definitive of predator behavior. A tagged juvenile salmonid that was in front of the physical barrier may swim upstream to get into the San Joaquin River. A tagged juvenile salmonid traveling sideways across medium to heavy flows suggests predator behavior.

(4) The overall behavior of the tagged juvenile salmonid and the different lines of evidence lead to a finding of predation, if such is the case.

(5) Velocity information (both speed and direction) was not available for review during initial fates assignments. Tagged salmonids that exhibited short-duration looping behavior, either in front of the physical barrier or in the scour hole, were assigned a fate based on their ultimate route, but a predation code of 1 ("unknown"). When velocity field information became available (May 2013), any fish with a "Predation = 1 ("unknown") code was reevaluated.

(6) A few tagged juvenile salmonids were examined with the velocity field to determine how their 2D tracks were influenced by the velocity field. All juvenile salmonids that exhibited purposeful downstream movements were assigned a predation of not eaten and assigned a fate based on their route selection. However, sudden direction changes associated with velocity direction and speed gradients became evident. For example, the juvenile Chinook salmon with tag 2987.03 made a directed downstream movement until it contacted an eddy in the scour hole that precipitated a strong turn to the right (Figure E-16).

(7) As opposed to earlier years, tagged juvenile salmonids that exhibited short-duration looping behavior, either in front of the physical barrier or in the scour hole, were assigned a fate based on their ultimate route unless specific predator-like behavior was observed (Figure E-17).

(8) After the velocity field information became available, all tagged juvenile salmonids that had predation with assigned fate "Unknown" were reevaluated. Some were checked to ensure the original fate that had been assigned was consistent with the velocity field. For example, the juvenile Chinook salmon with tag 2672.03 moved down in front of the physical barrier, traveled upstream, and made a complete loop, but was still assigned a fate of "San Joaquin River" (Figure E-17) because it did not exhibit predation behavior as defined in 2012.

(9) Predation behavior was defined in 2012 as clear, long upstream movements and/or looping behavior in areas where eddies would not have been expected to occur, or looping behavior for long periods of time (Figures E-18). If a tagged juvenile salmonid exited the HOR study area and returned later, this was considered evidence of predation, possibly outside the HOR study area; a longer period between exit and reentry gave stronger evidence of predation. Long residence time, greater than 8 hours, was considered strong evidence that a tagged juvenile salmonid was eaten and inside a predator.

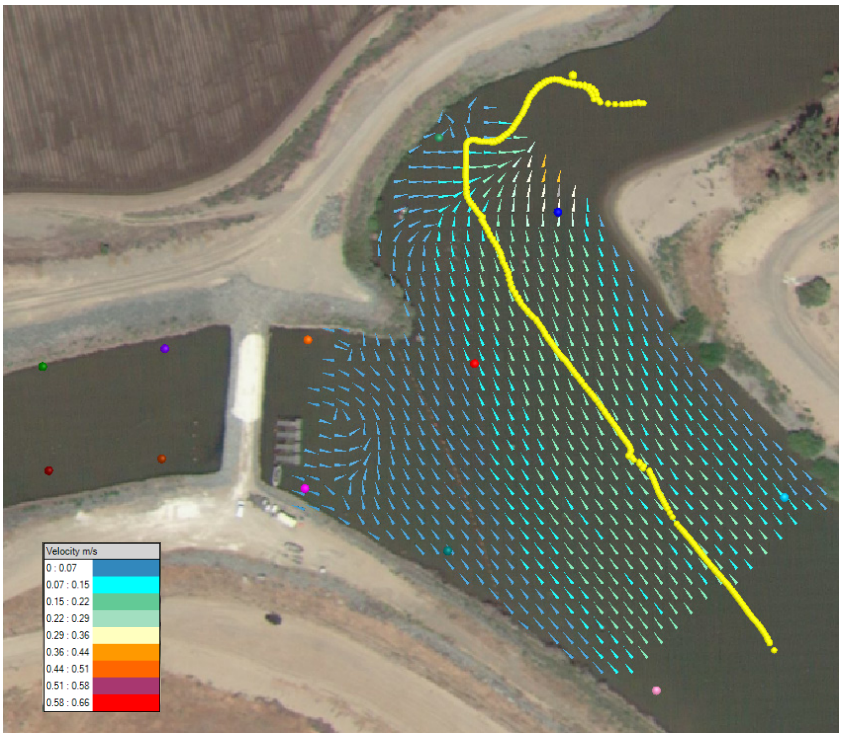
(10) The duration of looping behavior and where it took place played a role in determining whether tagged juvenile salmonids were coded as "Unknown" or "eaten." If the looping was limited in space and to a time period substantially less than 1 hour, then "Unknown" was assigned. Thus, the tag behavior guidelines (2012 guidelines, numbers (6) and (7) for assigning predation were more restrictive in 2012 than in other years. These restrictions took place because of the changes in the velocity field.

(11) Special note on two tagged juvenile salmonids traveling very close together: By itself, two tags traveling together could indicate schooling behavior or incidence of predation. It was suggested that additional finer scale tracking be implemented such as manual marking (of the sets of two and three fish together), and time series consideration to determine whether the points were always within 1 m of each other at all times. If the tags (tagged juveniles) were more than 1 m apart (positioning precision within the array was 1 m) at any one point, they were schooling. If they always were within 1 m of each other, this could be used as evidence of predation. For example, because looping behavior occurs that is not always with an eddy current or when upstream movement occurs, evidence exists of predation. In conjunction, the two tags traveling together increased the chances for predation and exceeding the new standard of proof that suggested "weight of evidence" (or such relevant evidence as a reasonable mind may accept as adequate to support a conclusion).

(12) If two or more tags (tagged juveniles) were traveling together (i.e., the positions of the two tracks were fully coincident), this was considered relevant evidence that predation of all tags had occurred. Alone, this was not sufficient to render a determination of predation, but this observation plus at least one more piece of evidence of predation (such as looping behavior in the absence of water eddies, upstream fish movement, or other) was convincing that this was predation (Bowen, pers. comm., 2013).

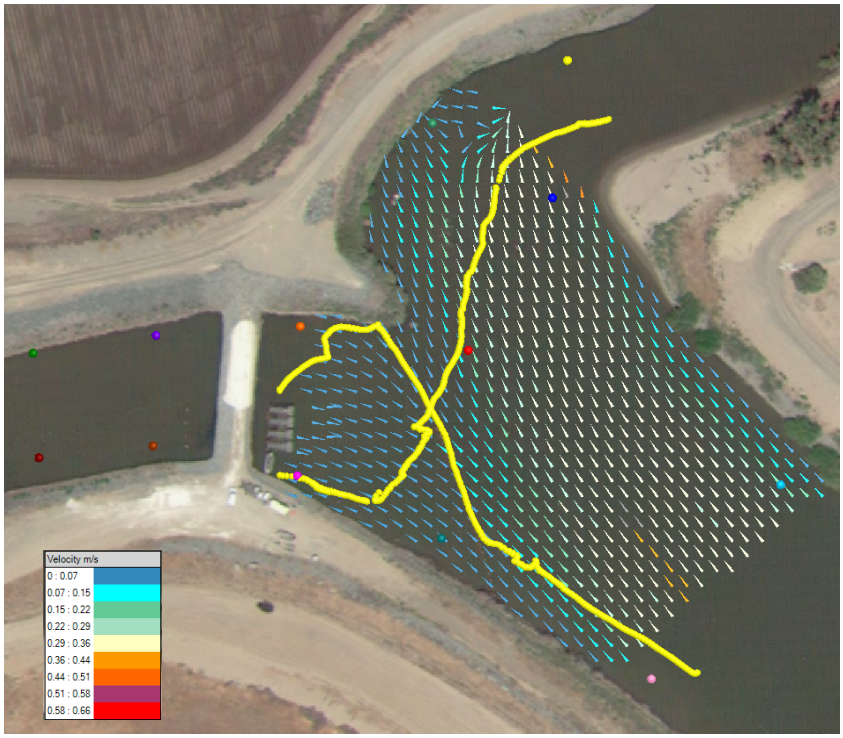
E.9 2012 TAGGED JUVENILE CHINOOK SALMON AND STEELHEAD FATE EXAMPLES

An example of an individual tagged juvenile Chinook salmon track from study year 2012 categorized not eaten by a predator which took the route of San Joaquin River is shown in Figure E-16, including flow field data for the time period that the tag was in the array. Figure E-17 shows a track of tagged juvenile Chinook salmon 2672.03 that makes a loop in front of the physical rock barrier, but does not move upstream, or cross areas of high velocity, so was categorized as having not been eaten by a predator. Figure E-18 shows a track of tagged juvenile Chinook salmon 4023.03, categorized as having been eaten by a predator, since it exhibits multiple loops and cross-flow behavior similar to a predator. Figure E-19 is the track of tagged predator (2154.14, striped bass of length 504 millimeters) showing looping behavior.



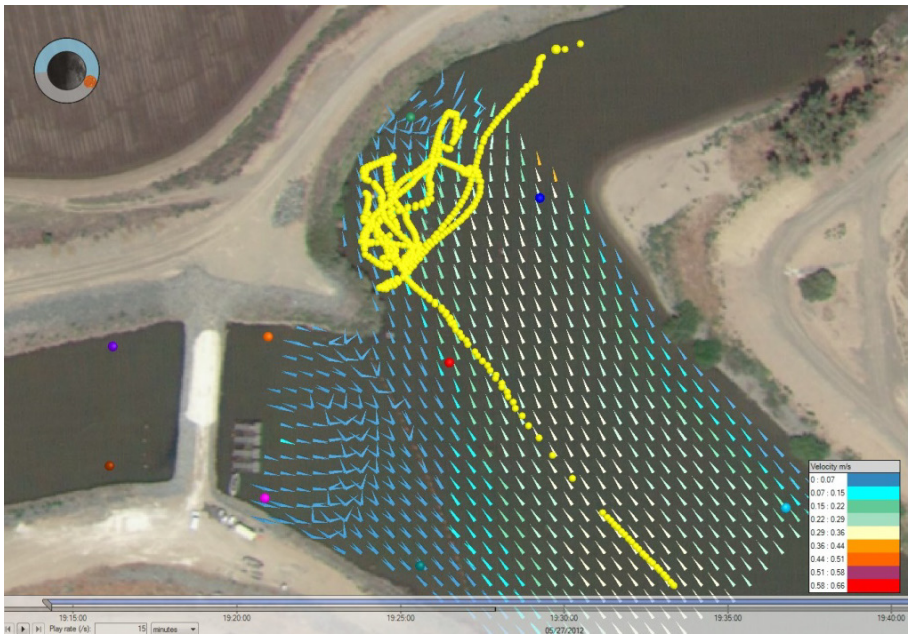
Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-16 **Juvenile Chinook Salmon Tag 2987.03 Moving Downstream in a Purposeful, Directed Way on 4/28/2012 with First Detection of 10:41:52 and Last Detection at 10:50:43 (residence time in area of HOR study area: 00:08:51 hours)**



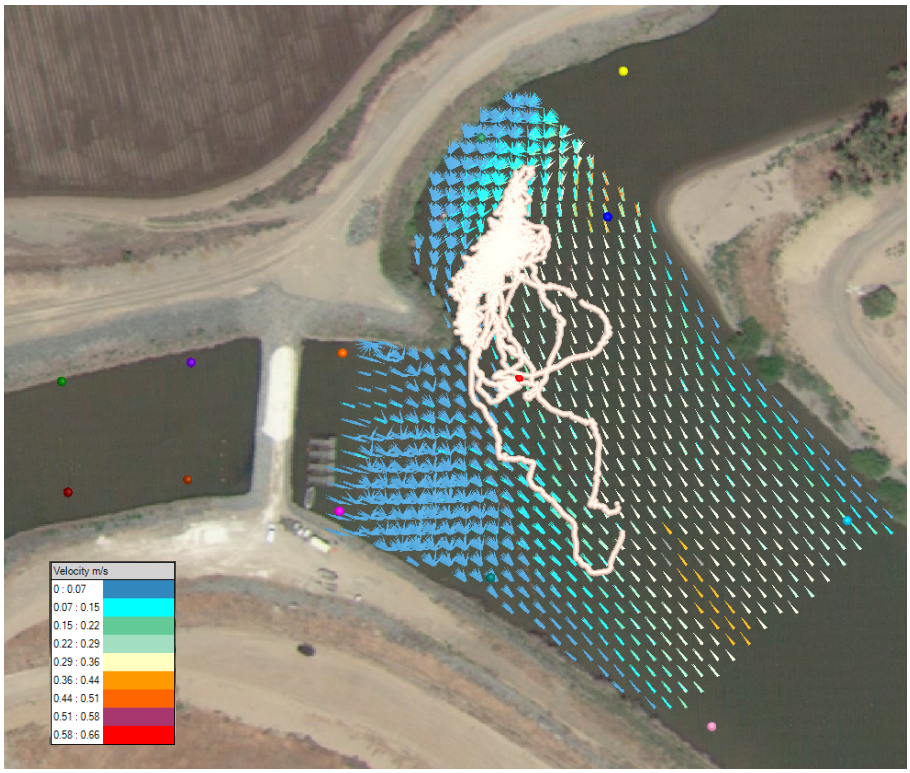
Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-17 **Juvenile Chinook Salmon Tag 2672.03 Designated as Not Having Been Eaten by a Predator, but Showing Loop in Front of Physical Barrier on 5/7/2012 at 21:58:00**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-18 **Tagged Juvenile Chinook Salmon (4023.03) Designated as Having Been Eaten by a Predatory Fish, Showing Extensive Looping in the Scour Hole Between 19:14 and 19:41, on May 27, 2012**



Source: Data compiled by Hydroacoustic Technology, Inc.

Figure E-19 **Track of Tagged Predator 2154.14 (Striped Bass, 504 millimeters), Showing Extensive Looping and Upstream Movement Between 16:00, May 16 and 04:30, May 17, 2012**

REFERENCES

Bowen, Mark D. Senior Fisheries Consultant. Turnpenny Horsfield Associates, Ashurst, UK. June 27, 2013—e-mail communication.

APPENDIX F

Model Fit and Weight Tables from Results of Predation Probability Generalized Linear Modeling

Table F-1
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2009, 2010, and 2012

Model Rank	Variables	AIC_c	w_i
1	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density + Temperature + Turbidity	1257.088	0.280
2	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature + Turbidity	1258.202	0.161
3	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density + Turbidity	1259.186	0.098
4	Intercept + Barrier + Light + Small-Fish Density + Turbidity	1259.653	0.078
5	Intercept + Barrier + Light + Small-Fish Density + Discharge + Temperature + Turbidity	1259.862	0.070
6	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature	1259.952	0.067
7	Intercept + Barrier + Light + Small-Fish Density + Discharge + Turbidity	1260.298	0.056
8	Intercept + Barrier + Light + Small-Fish Density + Temperature + Turbidity	1261.081	0.038
9	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density + Discharge + Turbidity	1261.081	0.038
10	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density + Temperature	1261.382	0.033
11	Intercept + Barrier + Light + Small-Fish Density + Discharge + Temperature	1262.019	0.024
12	Intercept + Barrier + Juvenile Length + Light + Temperature + Turbidity	1262.773	0.016
13	Intercept + Barrier + Juvenile Length + Light + Discharge + Temperature + Turbidity	1263.933	0.009
14	Intercept + Barrier + Light + Small-Fish Density + Discharge	1264.943	0.006
15	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density	1265.857	0.003
16	Intercept + Barrier + Juvenile Length + Light + Turbidity	1265.939	0.003
17	Intercept + Barrier + Juvenile Length + Light + Discharge + Temperature	1265.963	0.003
18	Intercept + Barrier + Juvenile Length + Light + Small-Fish Density + Discharge	1266.034	0.003
19	Intercept + Barrier + Light + Discharge + Temperature + Turbidity	1266.713	0.002
20	Intercept + Barrier + Light + Turbidity	1267.043	0.002
21	Intercept + Barrier + Juvenile Length + Light + Temperature	1267.405	0.002
22	Intercept + Barrier + Light + Discharge + Turbidity	1267.606	0.001
23	Intercept + Barrier + Juvenile Length + Light + Discharge + Turbidity	1267.879	0.001
24	Intercept + Barrier + Light + Small-Fish Density	1268.148	0.001
25	Intercept + Barrier + Light + Temperature + Turbidity	1268.251	0.001
26	Intercept + Barrier + Light + Small-Fish Density + Temperature	1269.051	0.001
27	Intercept + Barrier + Light + Discharge + Temperature	1269.248	0.001
28	Intercept + Juvenile Length + Light + Small-Fish Density + Temperature + Turbidity	1272.785	0.000
29	Intercept + Barrier + Light + Discharge	1272.806	0.000
30	Intercept + Barrier + Juvenile Length + Light	1273.149	0.000

Table F-1
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2009, 2010, and 2012

Model Rank	Variables	AIC_c	w_i
31	Intercept + Barrier + Juvenile Length + Light + Discharge	1273.395	0.000
32	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature + Turbidity	1273.890	0.000
33	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature	1275.699	0.000
34	Intercept + Barrier + Light	1276.572	0.000
35	Intercept + Juvenile Length + Light + Small-Fish Density + Temperature	1277.160	0.000
36	Intercept + Barrier + Light + Temperature	1277.225	0.000
37	Intercept + Juvenile Length + Light + Temperature + Turbidity	1280.126	0.000
38	Intercept + Juvenile Length + Light + Small-Fish Density + Turbidity	1280.576	0.000
39	Intercept + Juvenile Length + Light + Discharge + Temperature + Turbidity	1281.204	0.000
40	Intercept + Light + Small-Fish Density + Discharge + Temperature	1282.272	0.000
41	Intercept + Light + Small-Fish Density + Discharge + Temperature + Turbidity	1282.407	0.000
42	Intercept + Juvenile Length + Light + Discharge + Temperature	1282.498	0.000
43	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Turbidity	1282.580	0.000
44	Intercept + Juvenile Length + Light + Temperature	1283.827	0.000
45	Intercept + Juvenile Length + Light + Small-Fish Density	1284.094	0.000
46	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge	1284.993	0.000
47	Intercept + Light + Small-Fish Density + Discharge + Turbidity	1286.429	0.000
48	Intercept + Light + Small-Fish Density + Discharge	1287.210	0.000
49	Intercept + Light + Small-Fish Density + Turbidity	1287.671	0.000
50	Intercept + Light + Small-Fish Density + Temperature + Turbidity	1287.699	0.000
51	Intercept + Light + Small-Fish Density	1291.649	0.000
52	Intercept + Juvenile Length + Light + Turbidity	1291.671	0.000
53	Intercept + Light + Small-Fish Density + Temperature	1291.835	0.000
54	Intercept + Light + Discharge + Temperature	1293.663	0.000
55	Intercept + Juvenile Length + Light + Discharge + Turbidity	1293.687	0.000
56	Intercept + Barrier + Small-Fish Density + Discharge + Temperature + Turbidity	1294.070	0.000
57	Intercept + Juvenile Length + Light	1294.172	0.000
58	Intercept + Barrier + Juvenile Length + Small-Fish Density + Discharge + Temperature + Turbidity	1294.306	0.000
59	Intercept + Light + Discharge + Temperature + Turbidity	1294.475	0.000
60	Intercept + Juvenile Length + Light + Discharge	1295.399	0.000

Table F-1
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2009, 2010, and 2012

Model Rank	Variables	AIC_c	w_i
61	Intercept + Barrier + Juvenile Length + Small-Fish Density + Discharge + Temperature	1295.821	0.000
62	Intercept + Barrier + Small-Fish Density + Discharge + Temperature	1295.870	0.000
63	Intercept + Barrier + Juvenile Length + Small-Fish Density + Temperature + Turbidity	1296.635	0.000
64	Intercept + Barrier + Small-Fish Density + Temperature + Turbidity	1299.841	0.000
65	Intercept + Light + Discharge	1300.753	0.000
66	Intercept + Light + Discharge + Turbidity	1300.801	0.000
67	Intercept + Barrier + Small-Fish Density + Discharge + Turbidity	1301.469	0.000
68	Intercept + Barrier + Small-Fish Density + Turbidity	1301.696	0.000
69	Intercept + Light + Temperature + Turbidity	1302.133	0.000
70	Intercept + Barrier + Juvenile Length + Discharge + Temperature + Turbidity	1302.537	0.000
71	Intercept + Barrier + Discharge + Temperature + Turbidity	1303.089	0.000
72	Intercept + Light + Turbidity	1303.117	0.000
73	Intercept + Barrier + Juvenile Length + Small-Fish Density + Temperature	1303.132	0.000
74	Intercept + Barrier + Juvenile Length + Small-Fish Density + Turbidity	1303.183	0.000
75	Intercept + Barrier + Juvenile Length + Small-Fish Density + Discharge + Turbidity	1303.481	0.000
76	Intercept + Barrier + Juvenile Length + Discharge + Temperature	1304.095	0.000
77	Intercept + Barrier + Discharge + Temperature	1305.001	0.000
78	Intercept + Barrier + Juvenile Length + Temperature + Turbidity	1305.041	0.000
79	Intercept + Light + Temperature	1305.717	0.000
80	Intercept + Light	1306.420	0.000
81	Intercept + Barrier + Small-Fish Density + Discharge	1307.509	0.000
82	Intercept + Barrier + Juvenile Length + Small-Fish Density + Discharge	1309.477	0.000
83	Intercept + Barrier + Temperature + Turbidity	1309.770	0.000
84	Intercept + Barrier + Small-Fish Density + Temperature	1310.445	0.000
85	Intercept + Barrier + Juvenile Length + Temperature	1311.701	0.000
86	Intercept + Barrier + Discharge + Turbidity	1312.177	0.000
87	Intercept + Barrier + Turbidity	1312.654	0.000
88	Intercept + Juvenile Length + Small-Fish Density + Discharge + Temperature + Turbidity	1313.184	0.000
89	Intercept + Barrier + Small-Fish Density	1313.483	0.000
90	Intercept + Barrier + Juvenile Length + Small-Fish Density	1313.561	0.000

Table F-1
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2009, 2010, and 2012

Model Rank	Variables	AIC_c	w_i
91	Intercept + Barrier + Juvenile Length + Turbidity	1313.880	0.000
92	Intercept + Barrier + Juvenile Length + Discharge + Turbidity	1314.196	0.000
93	Intercept + Juvenile Length + Small-Fish Density + Discharge + Temperature	1314.892	0.000
94	Intercept + Juvenile Length + Small-Fish Density + Temperature + Turbidity	1315.423	0.000
95	Intercept + Small-Fish Density + Discharge + Temperature + Turbidity	1318.014	0.000
96	Intercept + Small-Fish Density + Discharge + Temperature	1318.210	0.000
97	Intercept + Barrier + Discharge	1318.320	0.000
98	Intercept + Barrier + Juvenile Length + Discharge	1320.336	0.000
99	Intercept + Barrier + Temperature	1321.232	0.000
100	Intercept + Juvenile Length + Small-Fish Density + Temperature	1321.995	0.000
101	Intercept + Juvenile Length + Discharge + Temperature + Turbidity	1323.356	0.000
102	Intercept + Juvenile Length + Discharge + Temperature	1324.321	0.000
103	Intercept + Barrier + Juvenile Length	1324.510	0.000
104	Intercept + Barrier	1325.166	0.000
105	Intercept + Juvenile Length + Temperature + Turbidity	1325.961	0.000
106	Intercept + Small-Fish Density + Temperature + Turbidity	1329.178	0.000
107	Intercept + Discharge + Temperature	1331.317	0.000
108	Intercept + Juvenile Length + Temperature	1331.499	0.000
109	Intercept + Discharge + Temperature + Turbidity	1331.983	0.000
110	Intercept + Juvenile Length + Small-Fish Density + Turbidity	1332.335	0.000
111	Intercept + Small-Fish Density + Discharge + Turbidity	1332.643	0.000
112	Intercept + Juvenile Length + Small-Fish Density + Discharge + Turbidity	1333.200	0.000
113	Intercept + Small-Fish Density + Discharge	1334.051	0.000
114	Intercept + Small-Fish Density + Turbidity	1335.117	0.000
115	Intercept + Juvenile Length + Small-Fish Density + Discharge	1335.232	0.000
116	Intercept + Small-Fish Density + Temperature	1335.725	0.000
117	Intercept + Juvenile Length + Small-Fish Density	1337.312	0.000
118	Intercept + Small-Fish Density	1341.005	0.000
119	Intercept + Temperature + Turbidity	1346.870	0.000
120	Intercept + Juvenile Length + Turbidity	1349.629	0.000

Table F-1
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2009, 2010, and 2012

Model Rank	Variables	AIC_c	w_i
121	Intercept + Juvenile Length + Discharge + Turbidity	1350.490	0.000
122	Intercept + Juvenile Length + Discharge	1351.311	0.000
123	Intercept + Discharge + Turbidity	1351.552	0.000
124	Intercept + Discharge	1351.677	0.000
125	Intercept + Temperature	1352.604	0.000
126	Intercept + Juvenile Length	1352.909	0.000
127	Intercept + Turbidity	1355.678	0.000
128	Intercept Only	1360.401	0.000

Notes: AIC_c = Akaike's Information Criterion adjusted for small sample sizes; *wi* = model weight; temperature = water temperature
Source: Present study

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
1	Intercept + Light + Temperature + Turbidity	590.436	0.080
2	Intercept + Light + Large-Fish Density (Down) + Temperature + Turbidity	590.978	0.061
3	Intercept + Juvenile Length + Light + Temperature + Turbidity	591.406	0.049
4	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	591.553	0.046
5	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	591.981	0.037
6	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	592.046	0.036
7	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	592.240	0.032
8	Intercept + Juvenile Length + Light + Turbidity	592.255	0.032
9	Intercept + Light + Large-Fish Density (Side) + Temperature + Turbidity	592.381	0.030
10	Intercept + Light + Discharge + Temperature + Turbidity	592.412	0.030
11	Intercept + Light + Small-Fish Density + Temperature + Turbidity	592.420	0.030
12	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Temperature + Turbidity	592.474	0.029
13	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	592.648	0.026
14	Intercept + Light + Turbidity	592.850	0.024
15	Intercept + Light + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	592.879	0.023
16	Intercept + Juvenile Length + Light + Small-Fish Density + Temperature + Turbidity	592.923	0.023
17	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	593.284	0.019
18	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Temperature + Turbidity	593.433	0.018
19	Intercept + Juvenile Length + Light + Discharge + Temperature + Turbidity	593.433	0.018
20	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	593.574	0.017
21	Intercept + Juvenile Length + Light + Discharge + Turbidity	593.617	0.016
22	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	593.619	0.016
23	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	593.621	0.016
24	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	593.763	0.015
25	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	593.977	0.014
26	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Turbidity	594.046	0.013
27	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Turbidity	594.164	0.012

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
28	Intercept + Light + Small-Fish Density + Turbidity	594.194	0.012
29	Intercept + Juvenile Length + Light + Small-Fish Density + Turbidity	594.278	0.012
30	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	594.283	0.012
31	Intercept + Light + Large-Fish Density (Down) + Turbidity	594.292	0.012
32	Intercept + Light + Discharge + Turbidity	594.345	0.011
33	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	594.351	0.011
34	Intercept + Light + Small-Fish Density + Discharge + Temperature + Turbidity	594.397	0.011
35	Intercept + Light + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	594.409	0.011
36	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge + Turbidity	594.684	0.010
37	Intercept + Light + Large-Fish Density (Side) + Turbidity	594.864	0.009
38	Intercept + Light + Large-Fish Density (Down) + Discharge + Turbidity	594.878	0.009
39	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	594.949	0.008
40	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature + Turbidity	594.952	0.008
41	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	595.106	0.008
42	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge + Turbidity	595.409	0.007
43	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	595.457	0.006
44	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	595.466	0.006
45	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	595.562	0.006
46	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Turbidity	595.602	0.006
47	Intercept + Light + Large-Fish Density (Side) + Discharge + Turbidity	595.766	0.006
48	Intercept + Light + Small-Fish Density + Discharge + Turbidity	595.881	0.005
49	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Turbidity	595.969	0.005
50	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Turbidity	596.040	0.005
51	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	596.080	0.005
52	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Turbidity	596.192	0.004
53	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Turbidity	596.205	0.004
54	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	596.382	0.004
55	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	596.679	0.004
56	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	596.779	0.003

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
57	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	596.894	0.003
58	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	596.906	0.003
59	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	596.938	0.003
60	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	597.329	0.003
61	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	597.470	0.002
62	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	597.554	0.002
63	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	598.039	0.002
64	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	598.926	0.001
65	Intercept + Juvenile Length + Light + Discharge + Temperature	603.689	0.000
66	Intercept + Light + Discharge + Temperature	604.298	0.000
67	Intercept + Juvenile Length + Light + Discharge	604.890	0.000
68	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Temperature	605.222	0.000
69	Intercept + Light + Small-Fish Density + Discharge + Temperature	605.629	0.000
70	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge + Temperature	605.660	0.000
71	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge + Temperature	605.662	0.000
72	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature	605.704	0.000
73	Intercept + Light + Large-Fish Density (Side) + Temperature	605.757	0.000
74	Intercept + Light + Large-Fish Density (Down) + Discharge + Temperature	606.124	0.000
75	Intercept + Light + Large-Fish Density (Side) + Discharge + Temperature	606.294	0.000
76	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	606.337	0.000
77	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	606.450	0.000
78	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature	606.544	0.000
79	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge	606.564	0.000
80	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge	606.875	0.000
81	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge	606.913	0.000
82	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature	607.037	0.000
83	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	607.366	0.000
84	Intercept + Light + Small-Fish Density + Discharge	607.490	0.000
85	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	607.582	0.000

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
86	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	607.654	0.000
87	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	607.674	0.000
88	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	607.693	0.000
89	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	607.695	0.000
90	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	608.174	0.000
91	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	608.358	0.000
92	Intercept + Light + Discharge	608.408	0.000
93	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge	608.519	0.000
94	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge	608.583	0.000
95	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	608.873	0.000
96	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature	609.107	0.000
97	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge	609.225	0.000
98	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	609.365	0.000
99	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	609.464	0.000
100	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge	609.500	0.000
101	Intercept + Light + Small-Fish Density + Temperature	609.861	0.000
102	Intercept + Light + Temperature	609.905	0.000
103	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Temperature	609.990	0.000
104	Intercept + Light + Large-Fish Density (Side) + Discharge	610.220	0.000
105	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature	610.330	0.000
106	Intercept + Light + Large-Fish Density (Down) + Temperature	610.334	0.000
107	Intercept + Light + Large-Fish Density (Down) + Discharge	610.405	0.000
108	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	610.436	0.000
109	Intercept + Juvenile Length + Light + Temperature	610.460	0.000
110	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	610.918	0.000
111	Intercept + Juvenile Length + Light + Small-Fish Density + Temperature	611.447	0.000
112	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density	611.648	0.000

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
113	Intercept + Temperature + Turbidity	611.892	0.000
114	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density	612.051	0.000
115	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	612.208	0.000
116	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density	612.293	0.000
117	Intercept + Juvenile Length + Light + Large-Fish Density (Side)	612.409	0.000
118	Intercept + Juvenile Length + Temperature + Turbidity	612.897	0.000
119	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	613.021	0.000
120	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density	613.099	0.000
121	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	613.223	0.000
122	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	613.279	0.000
123	Intercept + Large-Fish Density (Down) + Temperature + Turbidity	613.419	0.000
124	Intercept + Small-Fish Density + Temperature + Turbidity	613.735	0.000
125	Intercept + Large-Fish Density (Side) + Temperature + Turbidity	613.854	0.000
126	Intercept + Discharge + Temperature + Turbidity	613.896	0.000
127	Intercept + Juvenile Length + Small-Fish Density + Temperature + Turbidity	614.027	0.000
128	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	614.090	0.000
129	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	614.298	0.000
130	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	614.339	0.000
131	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side)	614.432	0.000
132	Intercept + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	614.528	0.000
133	Intercept + Juvenile Length + Large-Fish Density (Side) + Temperature + Turbidity	614.645	0.000
134	Intercept + Juvenile Length + Large-Fish Density (Down) + Temperature + Turbidity	614.733	0.000
135	Intercept + Juvenile Length + Discharge + Temperature + Turbidity	614.896	0.000
136	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	615.012	0.000
137	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	615.050	0.000
138	Intercept + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	615.385	0.000
139	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	615.428	0.000

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
140	Intercept + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	615.593	0.000
141	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	615.603	0.000
142	Intercept + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	615.726	0.000
143	Intercept + Small-Fish Density + Discharge + Temperature + Turbidity	615.735	0.000
144	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	615.824	0.000
145	Intercept + Juvenile Length + Small-Fish Density + Discharge + Temperature + Turbidity	616.021	0.000
146	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	616.325	0.000
147	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	616.336	0.000
148	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	616.480	0.000
149	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	616.612	0.000
150	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	616.890	0.000
151	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	617.499	0.000
152	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	617.742	0.000
153	Intercept + Juvenile Length + Discharge + Turbidity	618.337	0.000
154	Intercept + Light + Large-Fish Density (Side)	618.610	0.000
155	Intercept + Juvenile Length + Turbidity	618.716	0.000
156	Intercept + Juvenile Length + Light + Large-Fish Density (Down)	619.119	0.000
157	Intercept + Juvenile Length + Large-Fish Density (Side) + Turbidity	619.135	0.000
158	Intercept + Juvenile Length + Large-Fish Density (Side) + Temperature	619.994	0.000
159	Intercept + Turbidity	620.054	0.000
160	Intercept + Discharge + Turbidity	620.130	0.000
161	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge + Turbidity	620.287	0.000
162	Intercept + Juvenile Length + Small-Fish Density + Discharge + Turbidity	620.303	0.000
163	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge + Turbidity	620.353	0.000
164	Intercept + Juvenile Length + Large-Fish Density (Down) + Turbidity	620.394	0.000
165	Intercept + Juvenile Length + Discharge + Temperature	620.463	0.000
166	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side)	620.628	0.000
167	Intercept + Large-Fish Density (Side) + Temperature	620.701	0.000
168	Intercept + Juvenile Length + Small-Fish Density + Turbidity	620.729	0.000
169	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	620.975	0.000

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
170	Intercept + Discharge + Temperature	621.060	0.000
171	Intercept + Small-Fish Density + Turbidity	621.087	0.000
172	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Turbidity	621.157	0.000
173	Intercept + Large-Fish Density (Side) + Turbidity	621.256	0.000
174	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	621.285	0.000
175	Intercept + Small-Fish Density + Discharge + Turbidity	621.533	0.000
176	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	621.630	0.000
177	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge + Temperature	621.764	0.000
178	Intercept + Large-Fish Density (Down) + Discharge + Turbidity	621.878	0.000
179	Intercept + Large-Fish Density (Down) + Turbidity	622.001	0.000
180	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Temperature	622.015	0.000
181	Intercept + Large-Fish Density (Side) + Discharge + Turbidity	622.073	0.000
182	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	622.135	0.000
183	Intercept + Large-Fish Density (Side) + Small-Fish Density + Temperature	622.147	0.000
184	Intercept + Large-Fish Density (Side) + Small-Fish Density + Turbidity	622.231	0.000
185	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	622.234	0.000
186	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	622.329	0.000
187	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Turbidity	622.348	0.000
188	Intercept + Juvenile Length + Small-Fish Density + Discharge + Temperature	622.463	0.000
189	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge + Temperature	622.486	0.000
190	Intercept + Large-Fish Density (Side) + Discharge + Temperature	622.504	0.000
191	Intercept + Large-Fish Density (Down) + Small-Fish Density + Turbidity	622.706	0.000
192	Intercept + Small-Fish Density + Discharge + Temperature	622.723	0.000
193	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	622.958	0.000
194	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	623.020	0.000
195	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	623.025	0.000
196	Intercept + Large-Fish Density (Down) + Discharge + Temperature	623.032	0.000
197	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	623.223	0.000
198	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	623.530	0.000
199	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	623.547	0.000

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
200	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	623.614	0.000
201	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	623.614	0.000
202	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	623.786	0.000
203	Intercept + Light + Small-Fish Density	623.846	0.000
204	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	623.901	0.000
205	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	624.048	0.000
206	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	624.069	0.000
207	Intercept + Temperature	624.182	0.000
208	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	624.249	0.000
209	Intercept + Juvenile Length + Large-Fish Density (Down) + Temperature	624.415	0.000
210	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	624.485	0.000
211	Intercept + Juvenile Length + Discharge	624.532	0.000
212	Intercept + Juvenile Length + Temperature	624.680	0.000
213	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	624.740	0.000
214	Intercept + Large-Fish Density (Down) + Temperature	624.808	0.000
215	Intercept + Large-Fish Density (Down) + Small-Fish Density + Temperature	624.827	0.000
216	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	624.924	0.000
217	Intercept + Small-Fish Density + Temperature	625.022	0.000
218	Intercept + Juvenile Length + Light + Small-Fish Density	625.191	0.000
219	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	625.557	0.000
220	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	625.607	0.000
221	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Temperature	625.673	0.000
222	Intercept + Juvenile Length + Small-Fish Density + Temperature	626.314	0.000
223	Intercept + Juvenile Length + Small-Fish Density + Discharge	626.336	0.000
224	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge	626.406	0.000
225	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge	626.473	0.000
226	Intercept + Light + Large-Fish Density (Down)	626.808	0.000
227	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge	627.976	0.000

Table F-2
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Chinook Salmon at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
228	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge	628.241	0.000
229	Intercept + Small-Fish Density + Discharge	628.244	0.000
230	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	628.424	0.000
231	Intercept + Discharge	629.147	0.000
232	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge	629.388	0.000
233	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	630.003	0.000
234	Intercept + Juvenile Length + Large-Fish Density (Side)	630.080	0.000
235	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge	630.205	0.000
236	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density	630.248	0.000
237	Intercept + Large-Fish Density (Down) + Discharge	631.107	0.000
238	Intercept + Large-Fish Density (Side) + Discharge	631.159	0.000
239	Intercept + Large-Fish Density (Down) + Small-Fish Density	631.177	0.000
240	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	631.291	0.000
241	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density	631.354	0.000
242	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	631.462	0.000
243	Intercept + Large-Fish Density (Side) + Small-Fish Density	631.917	0.000
244	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side)	631.943	0.000
245	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	632.264	0.000
246	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	633.084	0.000
247	Intercept + Juvenile Length + Light	634.876	0.000
248	Intercept + Juvenile Length + Large-Fish Density (Down)	636.158	0.000
249	Intercept + Large-Fish Density (Side)	637.589	0.000
250	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side)	639.383	0.000
251	Intercept + Light	643.386	0.000
252	Intercept + Large-Fish Density (Down)	644.650	0.000
253	Intercept + Small-Fish Density	645.493	0.000
254	Intercept + Juvenile Length + Small-Fish Density	646.461	0.000
255	Intercept + Juvenile Length	654.921	0.000
256	Intercept Only	664.049	0.000

Notes: AIC_c = Akaike's Information Criterion adjusted for small sample sizes; *wi* = model weight; temperature = water temperature
Source: Present study

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
1	Intercept + Light + Discharge + Temperature	190.054	0.035
2	Intercept + Light + Small-Fish Density + Discharge + Temperature	190.575	0.027
3	Intercept + Light + Temperature	190.730	0.025
4	Intercept + Light + Discharge + Temperature + Turbidity	191.236	0.019
5	Intercept + Light + Small-Fish Density + Discharge	191.689	0.015
6	Intercept + Light	191.690	0.015
7	Intercept + Light + Small-Fish Density + Temperature	191.694	0.015
8	Intercept + Light + Small-Fish Density	191.720	0.015
9	Intercept + Small-Fish Density	191.881	0.014
10	Intercept + Light + Large-Fish Density (Down) + Discharge + Temperature	191.934	0.014
11	Intercept + Large-Fish Density (Side) + Small-Fish Density	192.027	0.013
12	Intercept + Juvenile Length + Light + Discharge + Temperature	192.059	0.013
13	Intercept + Light + Large-Fish Density (Side)	192.071	0.013
14	Intercept + Temperature	192.120	0.012
15	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density	192.120	0.012
16	Intercept only	192.147	0.012
17	Intercept + Light + Large-Fish Density (Side) + Discharge + Temperature	192.155	0.012
18	Intercept + Large-Fish Density (Side)	192.277	0.011
19	Intercept + Light + Discharge	192.343	0.011
20	Intercept + Light + Large-Fish Density (Side) + Temperature	192.369	0.011
21	Intercept + Small-Fish Density + Temperature	192.556	0.010
22	Intercept + Light + Small-Fish Density + Discharge + Temperature + Turbidity	192.605	0.010
23	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	192.689	0.009
24	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	192.711	0.009
25	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature	192.722	0.009
26	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge	192.772	0.009
27	Intercept + Juvenile Length + Light + Temperature	192.810	0.009
28	Intercept + Light + Temperature + Turbidity	192.816	0.009
29	Intercept + Light + Large-Fish Density (Down) + Temperature	192.828	0.009
30	Intercept + Small-Fish Density + Discharge	192.984	0.008

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
31	Intercept + Light + Discharge + Turbidity	193.004	0.008
32	Intercept + Small-Fish Density + Turbidity	193.005	0.008
33	Intercept + Discharge + Temperature	193.013	0.008
34	Intercept + Small-Fish Density + Discharge + Temperature	193.151	0.007
35	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature	193.201	0.007
36	Intercept + Light + Large-Fish Density (Side) + Discharge	193.218	0.007
37	Intercept + Light + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	193.251	0.007
38	Intercept + Small-Fish Density + Temperature + Turbidity	193.256	0.007
39	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature	193.320	0.007
40	Intercept + Juvenile Length + Light + Discharge + Temperature + Turbidity	193.327	0.007
41	Intercept + Large-Fish Density (Side) + Temperature	193.345	0.007
42	Intercept + Light + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	193.373	0.007
43	Intercept + Light + Large-Fish Density (Side) + Discharge + Turbidity	193.462	0.006
44	Intercept + Light + Large-Fish Density (Down) + Discharge	193.466	0.006
45	Intercept + Light + Turbidity	193.490	0.006
46	Intercept + Light + Large-Fish Density (Side) + Turbidity	193.519	0.006
47	Intercept + Light + Large-Fish Density (Down)	193.545	0.006
48	Intercept + Light + Small-Fish Density + Temperature + Turbidity	193.568	0.006
49	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge	193.593	0.006
50	Intercept + Large-Fish Density (Side) + Small-Fish Density + Temperature	193.616	0.006
51	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	193.626	0.006
52	Intercept + Discharge	193.629	0.006
53	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density	193.639	0.006
54	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	193.658	0.006
55	Intercept + Light + Small-Fish Density + Turbidity	193.697	0.006
56	Intercept + Light + Small-Fish Density + Discharge + Turbidity	193.716	0.006
57	Intercept + Juvenile Length + Light	193.729	0.006
58	Intercept + Large-Fish Density (Side) + Small-Fish Density + Turbidity	193.768	0.005
59	Intercept + Juvenile Length + Light + Small-Fish Density	193.809	0.005
60	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge	193.811	0.005

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
61	Intercept + Juvenile Length + Light + Small-Fish Density + Temperature	193.815	0.005
62	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge	193.817	0.005
63	Intercept + Large-Fish Density (Down) + Small-Fish Density	193.828	0.005
64	Intercept + Large-Fish Density (Down)	193.851	0.005
65	Intercept + Temperature + Turbidity	193.946	0.005
66	Intercept + Juvenile Length + Small-Fish Density	193.953	0.005
67	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge + Temperature	194.038	0.005
68	Intercept + Large-Fish Density (Side) + Discharge	194.072	0.005
69	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	194.090	0.005
70	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density	194.120	0.005
71	Intercept + Juvenile Length	194.127	0.005
72	Intercept + Juvenile Length + Temperature	194.136	0.005
73	Intercept + Large-Fish Density (Down) + Temperature	194.148	0.004
74	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side)	194.156	0.004
75	Intercept + Juvenile Length + Light + Large-Fish Density (Side)	194.159	0.004
76	Intercept + Turbidity	194.188	0.004
77	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge + Temperature	194.197	0.004
78	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density	194.220	0.004
79	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Turbidity	194.249	0.004
80	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side)	194.297	0.004
81	Intercept + Large-Fish Density (Side) + Turbidity	194.303	0.004
82	Intercept + Juvenile Length + Large-Fish Density (Side)	194.309	0.004
83	Intercept + Juvenile Length + Light + Discharge	194.332	0.004
84	Intercept + Large-Fish Density (Down) + Small-Fish Density + Temperature	194.354	0.004
85	Intercept + Light + Large-Fish Density (Side) + Temperature + Turbidity	194.362	0.004
86	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	194.459	0.004
87	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Temperature	194.486	0.004
88	Intercept + Small-Fish Density + Discharge + Temperature + Turbidity	194.499	0.004
89	Intercept + Small-Fish Density + Discharge + Turbidity	194.535	0.004
90	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	194.552	0.004

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
91	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	194.615	0.004
92	Intercept + Juvenile Length + Small-Fish Density + Temperature	194.656	0.003
93	Intercept + Large-Fish Density (Side) + Discharge + Temperature	194.698	0.003
94	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	194.701	0.003
95	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	194.744	0.003
96	Intercept + Large-Fish Density (Down) + Discharge + Temperature	194.756	0.003
97	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Temperature + Turbidity	194.780	0.003
98	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	194.799	0.003
99	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	194.825	0.003
100	Intercept + Large-Fish Density (Down) + Discharge	194.860	0.003
101	Intercept + Light + Large-Fish Density (Down) + Discharge + Turbidity	194.864	0.003
102	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	194.866	0.003
103	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	194.867	0.003
104	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	194.880	0.003
105	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	194.923	0.003
106	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Temperature	194.925	0.003
107	Intercept + Light + Large-Fish Density (Down) + Temperature + Turbidity	194.926	0.003
108	Intercept + Juvenile Length + Light + Temperature + Turbidity	194.927	0.003
109	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge	194.928	0.003
110	Intercept + Juvenile Length + Discharge + Temperature	194.958	0.003
111	Intercept + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	195.005	0.003
112	Intercept + Discharge + Temperature + Turbidity	195.079	0.003
113	Intercept + Juvenile Length + Small-Fish Density + Discharge	195.083	0.003
114	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge	195.085	0.003
115	Intercept + Juvenile Length + Light + Discharge + Turbidity	195.088	0.003
116	Intercept + Large-Fish Density (Down) + Small-Fish Density + Turbidity	195.094	0.003
117	Intercept + Juvenile Length + Small-Fish Density + Turbidity	195.106	0.003
118	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	195.127	0.003
119	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	195.252	0.003
120	Intercept + Juvenile Length + Small-Fish Density + Discharge + Temperature	195.267	0.003

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
121	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge	195.279	0.003
122	Intercept + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	195.294	0.003
123	Intercept + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	195.300	0.003
124	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature	195.338	0.002
125	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	195.378	0.002
126	Intercept + Juvenile Length + Small-Fish Density + Temperature + Turbidity	195.385	0.002
127	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	195.390	0.002
128	Intercept + Juvenile Length + Large-Fish Density (Side) + Temperature	195.405	0.002
129	Intercept + Large-Fish Density (Side) + Temperature + Turbidity	195.415	0.002
130	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	195.435	0.002
131	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	195.446	0.002
132	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	195.463	0.002
133	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature	195.473	0.002
134	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	195.505	0.002
135	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	195.527	0.002
136	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	195.536	0.002
137	Intercept + Light + Large-Fish Density (Down) + Turbidity	195.539	0.002
138	Intercept + Juvenile Length + Discharge	195.568	0.002
139	Intercept + Juvenile Length + Light + Turbidity	195.578	0.002
140	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge	195.587	0.002
141	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Discharge + Turbidity	195.607	0.002
142	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	195.617	0.002
143	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	195.618	0.002
144	Intercept + Juvenile Length + Light + Large-Fish Density (Down)	195.645	0.002
145	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Turbidity	195.648	0.002
146	Intercept + Discharge + Turbidity	195.685	0.002
147	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	195.689	0.002
148	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Turbidity	195.714	0.002
149	Intercept + Juvenile Length + Light + Small-Fish Density + Temperature + Turbidity	195.719	0.002
150	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge	195.722	0.002

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
151	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Temperature	195.739	0.002
152	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	195.750	0.002
153	Intercept + Large-Fish Density (Down) + Turbidity	195.765	0.002
154	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density	195.767	0.002
155	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density	195.814	0.002
156	Intercept + Juvenile Length + Light + Small-Fish Density + Turbidity	195.815	0.002
157	Intercept + Large-Fish Density (Down) + Temperature + Turbidity	195.856	0.002
158	Intercept + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	195.872	0.002
159	Intercept + Juvenile Length + Light + Small-Fish Density + Discharge + Turbidity	195.872	0.002
160	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Turbidity	195.892	0.002
161	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	195.903	0.002
162	Intercept + Juvenile Length + Large-Fish Density (Down)	195.918	0.002
163	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density	195.930	0.002
164	Intercept + Juvenile Length + Temperature + Turbidity	195.955	0.002
165	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge	195.967	0.002
166	Intercept + Large-Fish Density (Side) + Discharge + Turbidity	196.023	0.002
167	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge	196.087	0.002
168	Intercept + Juvenile Length + Turbidity	196.186	0.002
169	Intercept + Juvenile Length + Large-Fish Density (Down) + Temperature	196.214	0.002
170	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	196.222	0.002
171	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side)	196.278	0.002
172	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	196.292	0.002
173	Intercept + Juvenile Length + Large-Fish Density (Side) + Turbidity	196.372	0.001
174	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Turbidity	196.376	0.001
175	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side)	196.378	0.001
176	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	196.386	0.001
177	Intercept + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	196.475	0.001
178	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Temperature	196.477	0.001
179	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Temperature + Turbidity	196.516	0.001
180	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	196.584	0.001

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
181	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	196.617	0.001
182	Intercept + Juvenile Length + Small-Fish Density + Discharge + Temperature + Turbidity	196.642	0.001
183	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	196.647	0.001
184	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	196.651	0.001
185	Intercept + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	196.655	0.001
186	Intercept + Juvenile Length + Small-Fish Density + Discharge + Turbidity	196.660	0.001
187	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge + Temperature	196.705	0.001
188	Intercept + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	196.722	0.001
189	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	196.724	0.001
190	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	196.734	0.001
191	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	196.789	0.001
192	Intercept + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	196.794	0.001
193	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	196.798	0.001
194	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge + Temperature	196.822	0.001
195	Intercept + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	196.827	0.001
196	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	196.888	0.001
197	Intercept + Large-Fish Density (Down) + Discharge + Turbidity	196.907	0.001
198	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	196.909	0.001
199	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	196.939	0.001
200	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge	196.942	0.001
201	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	196.951	0.001
202	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Discharge + Turbidity	197.012	0.001
203	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	197.024	0.001
204	Intercept + Juvenile Length + Discharge + Temperature + Turbidity	197.036	0.001
205	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	197.049	0.001
206	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Temperature + Turbidity	197.050	0.001
207	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	197.069	0.001

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

Model Rank	Variables	AIC_c	w_i
208	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	197.160	0.001
209	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge	197.211	0.001
210	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Turbidity	197.223	0.001
211	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature	197.274	0.001
212	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature	197.388	0.001
213	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	197.452	0.001
214	Intercept + Juvenile Length + Light + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	197.462	0.001
215	Intercept + Juvenile Length + Large-Fish Density (Side) + Temperature + Turbidity	197.490	0.001
216	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	197.525	0.001
217	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature	197.533	0.001
218	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Temperature + Turbidity	197.560	0.001
219	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	197.584	0.001
220	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	197.598	0.001
221	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	197.607	0.001
222	Intercept + Juvenile Length + Discharge + Turbidity	197.659	0.001
223	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Turbidity	197.665	0.001
224	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	197.683	0.001
225	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge	197.685	0.001
226	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	197.771	0.001
227	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	197.787	0.001
228	Intercept + Juvenile Length + Large-Fish Density (Down) + Turbidity	197.858	0.001
229	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Turbidity	197.868	0.001
230	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Turbidity	197.873	0.001
231	Intercept + Juvenile Length + Large-Fish Density (Down) + Temperature + Turbidity	197.948	0.001
232	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge	198.003	0.001
233	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	198.005	0.001
234	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	198.056	0.001
235	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge + Turbidity	198.083	0.001

Table F-3
Model Fit (AIC_c) and Weight (w_i) for the Generalized Linear Modeling of Predation Probability of Acoustically Tagged Juvenile Steelhead at the Head of Old River in 2011 and 2012

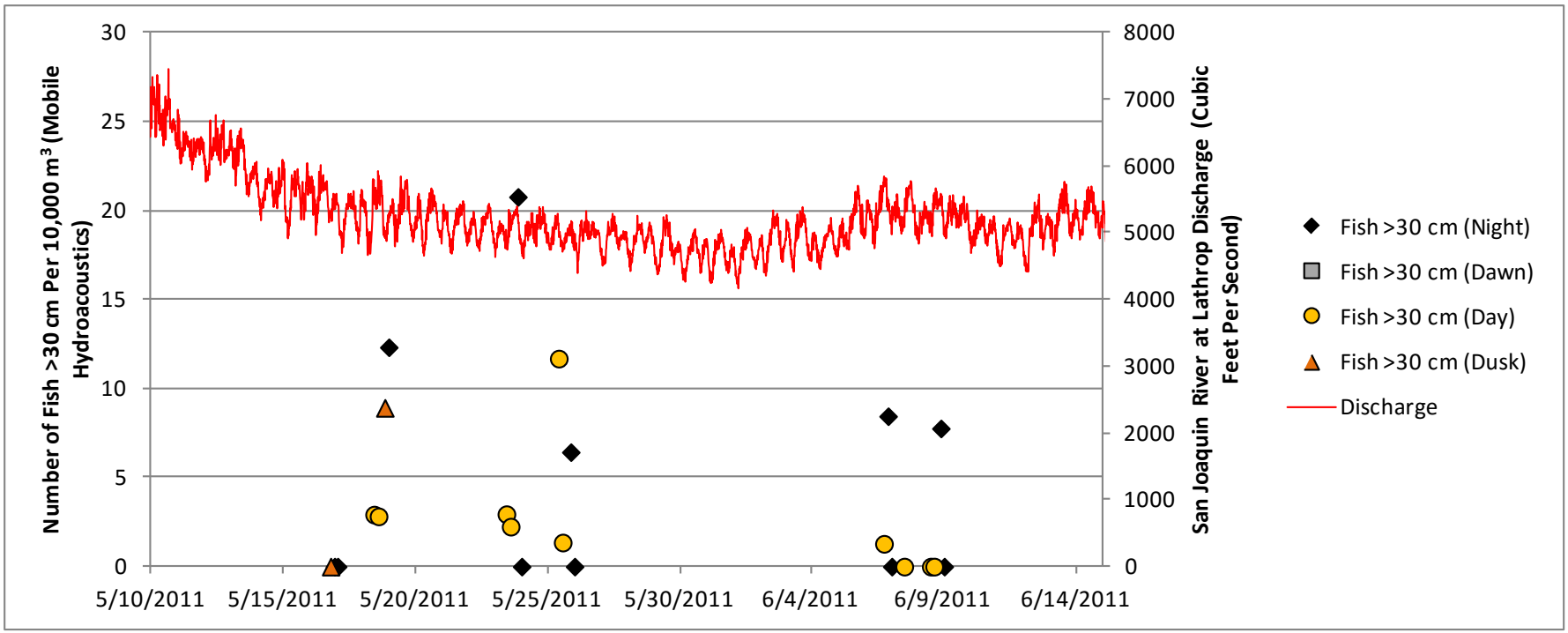
Model Rank	Variables	AIC_c	w_i
236	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	198.444	0.001
237	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Turbidity	198.492	0.001
238	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	198.614	0.000
239	Intercept + Juvenile Length + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	198.651	0.000
240	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature	198.740	0.000
241	Intercept + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	198.760	0.000
242	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge + Turbidity	198.805	0.000
243	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge + Temperature + Turbidity	198.815	0.000
244	Intercept + Juvenile Length + Large-Fish Density (Down) + Small-Fish Density + Discharge + Temperature + Turbidity	198.824	0.000
245	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	198.827	0.000
246	Intercept + Juvenile Length + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	198.860	0.000
247	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	198.933	0.000
248	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature	198.954	0.000
249	Intercept + Juvenile Length + Large-Fish Density (Down) + Discharge + Turbidity	199.017	0.000
250	Intercept + Juvenile Length + Light + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	199.019	0.000
251	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Temperature + Turbidity	199.066	0.000
252	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Temperature + Turbidity	199.640	0.000
253	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Turbidity	199.763	0.000
254	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Turbidity	200.131	0.000
255	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Small-Fish Density + Discharge + Temperature + Turbidity	200.811	0.000
256	Intercept + Juvenile Length + Large-Fish Density (Down) + Large-Fish Density (Side) + Discharge + Temperature + Turbidity	200.882	0.000

Notes: AIC_c = Akaike's Information Criterion adjusted for small sample sizes; *wi* = model weight; temperature = water temperature
Source: Present study

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APPENDIX G

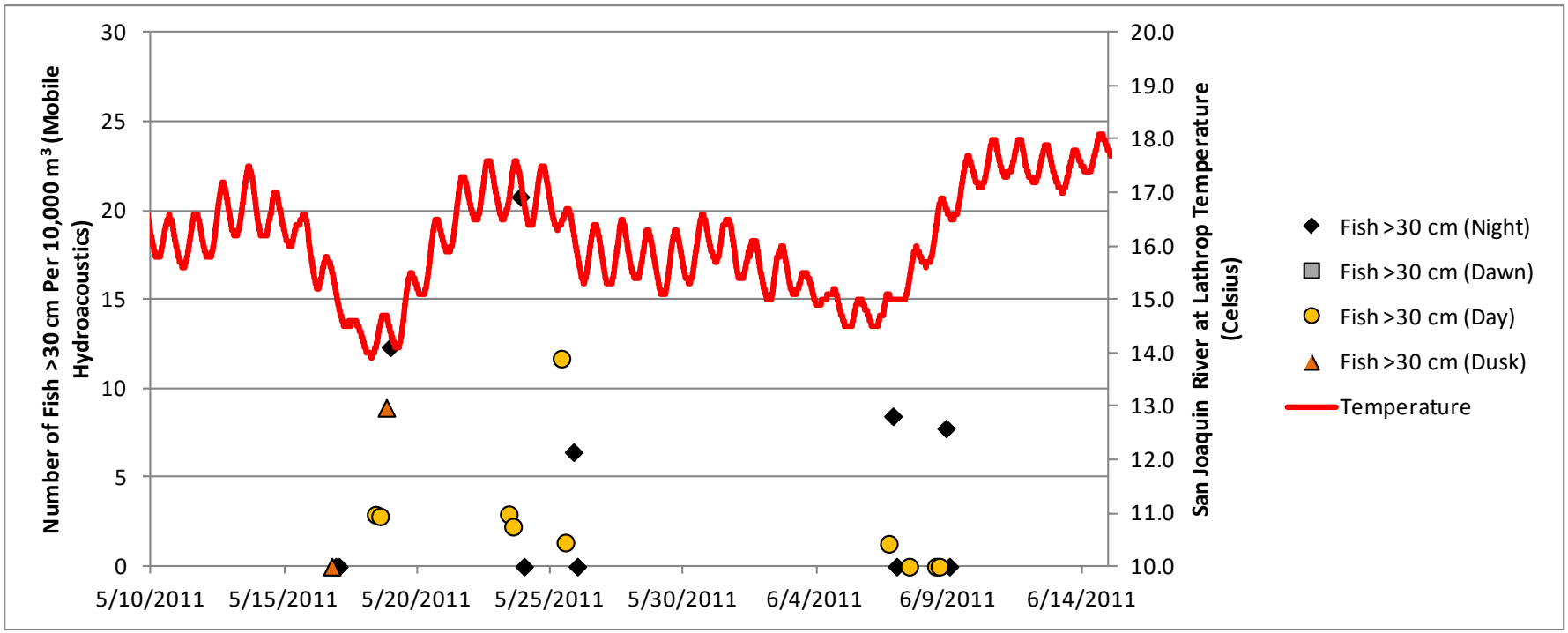
Plots of Environmental Variables and Large-Fish Density from Mobile Hydroacoustic Surveys



Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

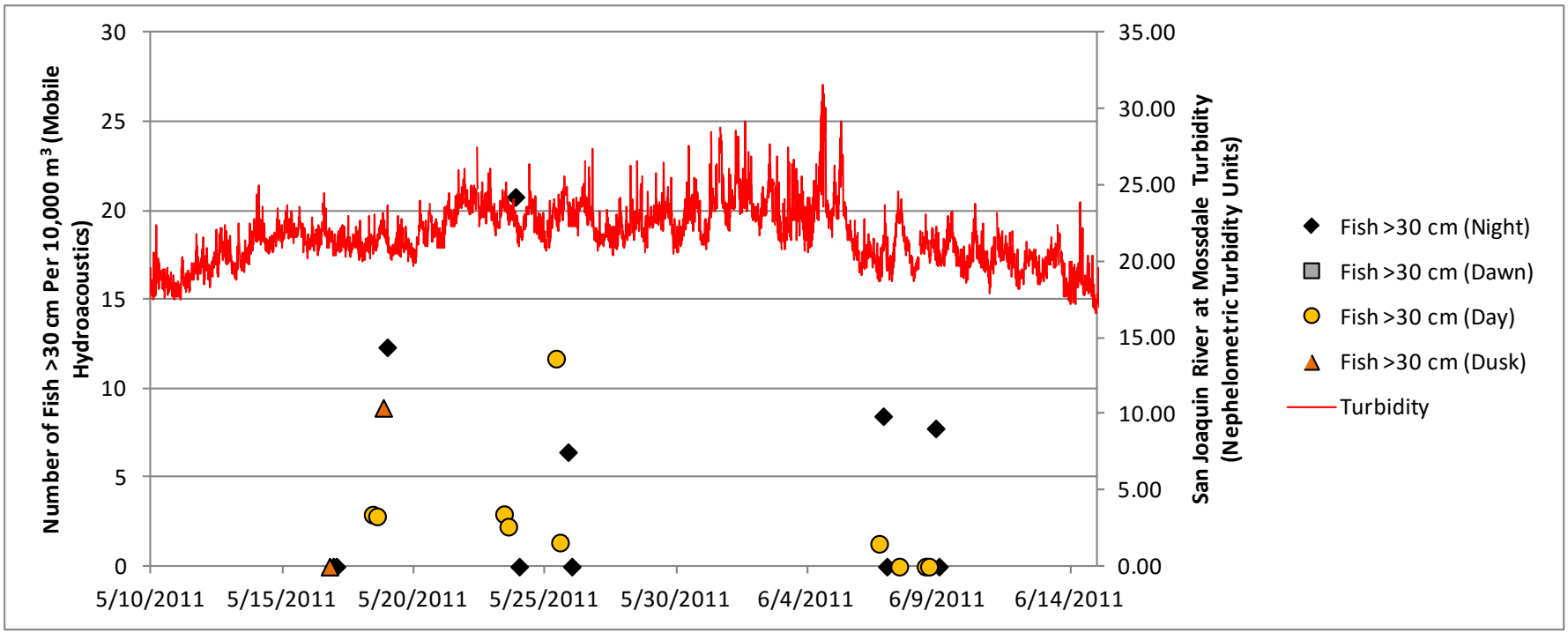
Figure G-1 **Estimated Large-Fish Density in Relation to River Discharge and Photoperiod Observed During Down-Looking Mobile Hydroacoustic Surveys in 2011**



Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-2 **Estimated Large-Fish Density in Relation to Water Temperature and Photoperiod Observed During Down-Looking Mobile Hydroacoustic Surveys in 2011**

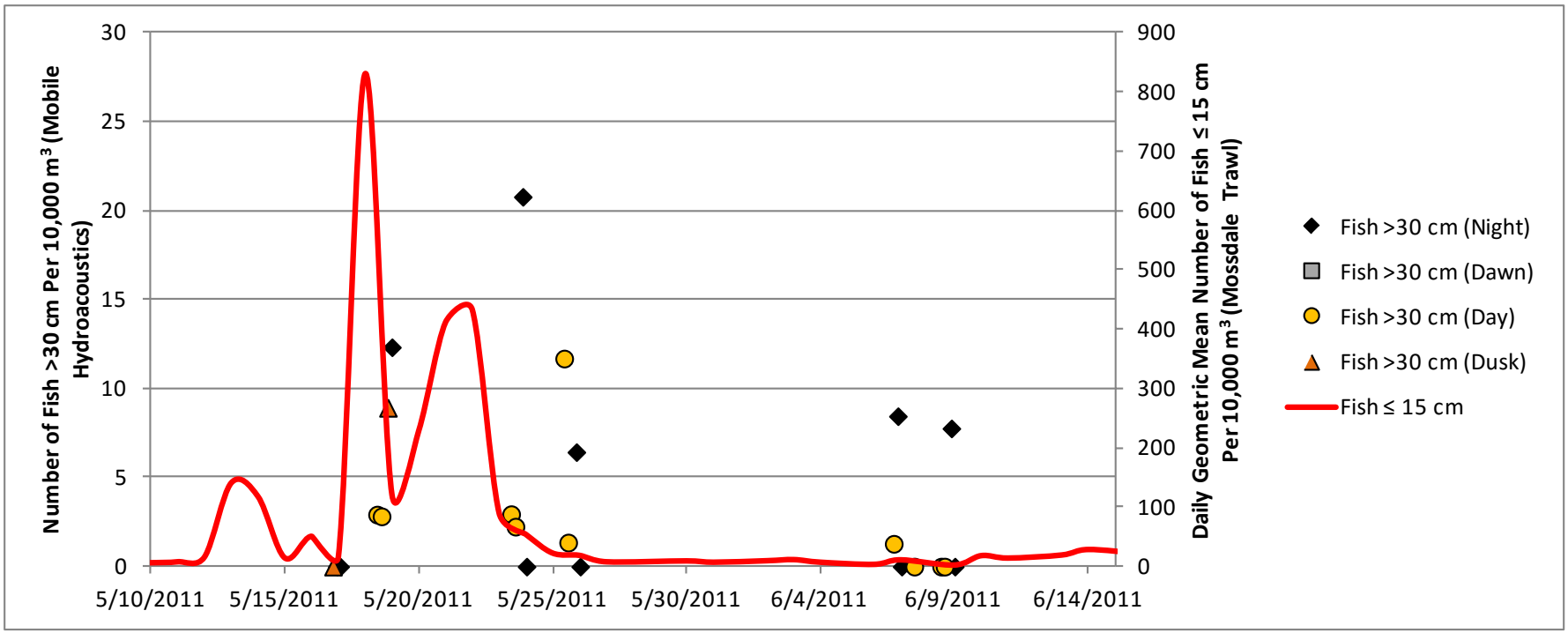


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-3

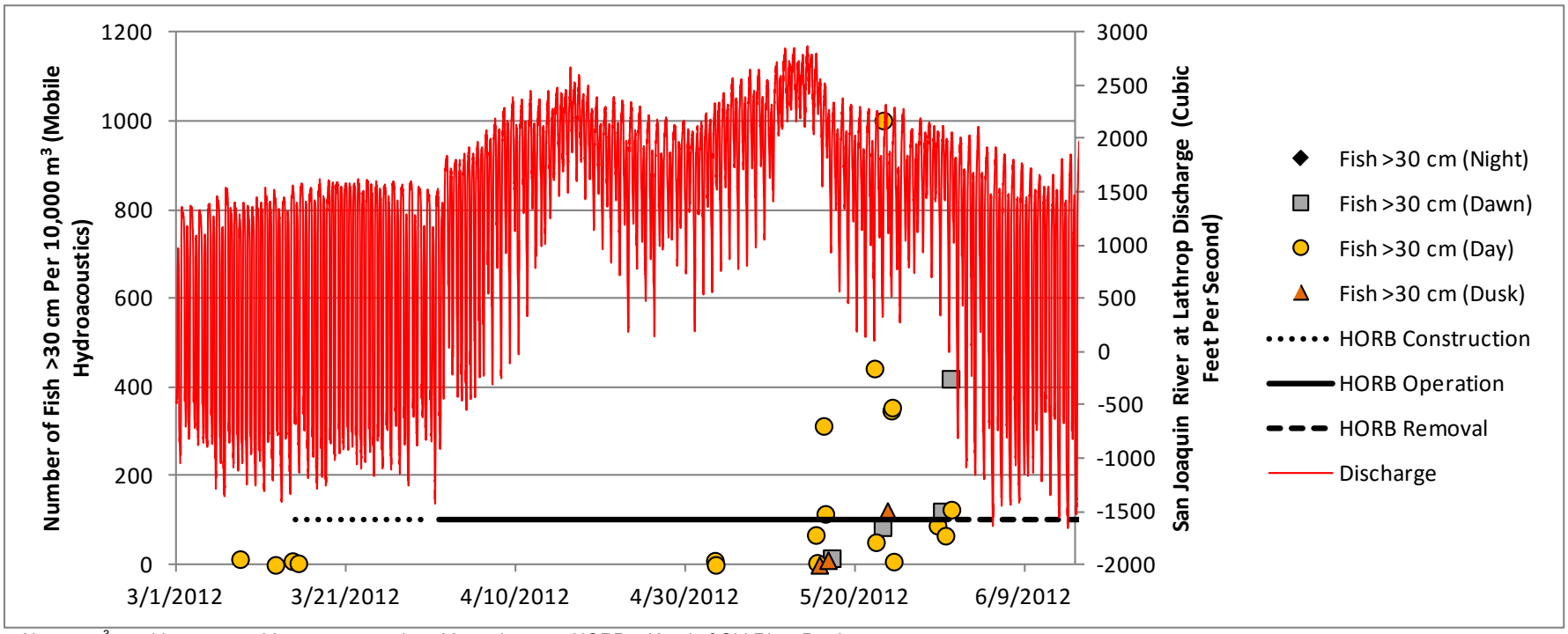
Estimated Large-Fish Density in Relation to Turbidity and Photoperiod Observed During Down-Looking Mobile Hydroacoustic Surveys in 2011



Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; ≤15 cm = less than or equal to 15 centimeters

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-4 **Estimated Large-Fish Density in Relation to Small-Fish Density and Photoperiod Observed During Down-Looking Mobile Hydroacoustic Surveys in 2011**

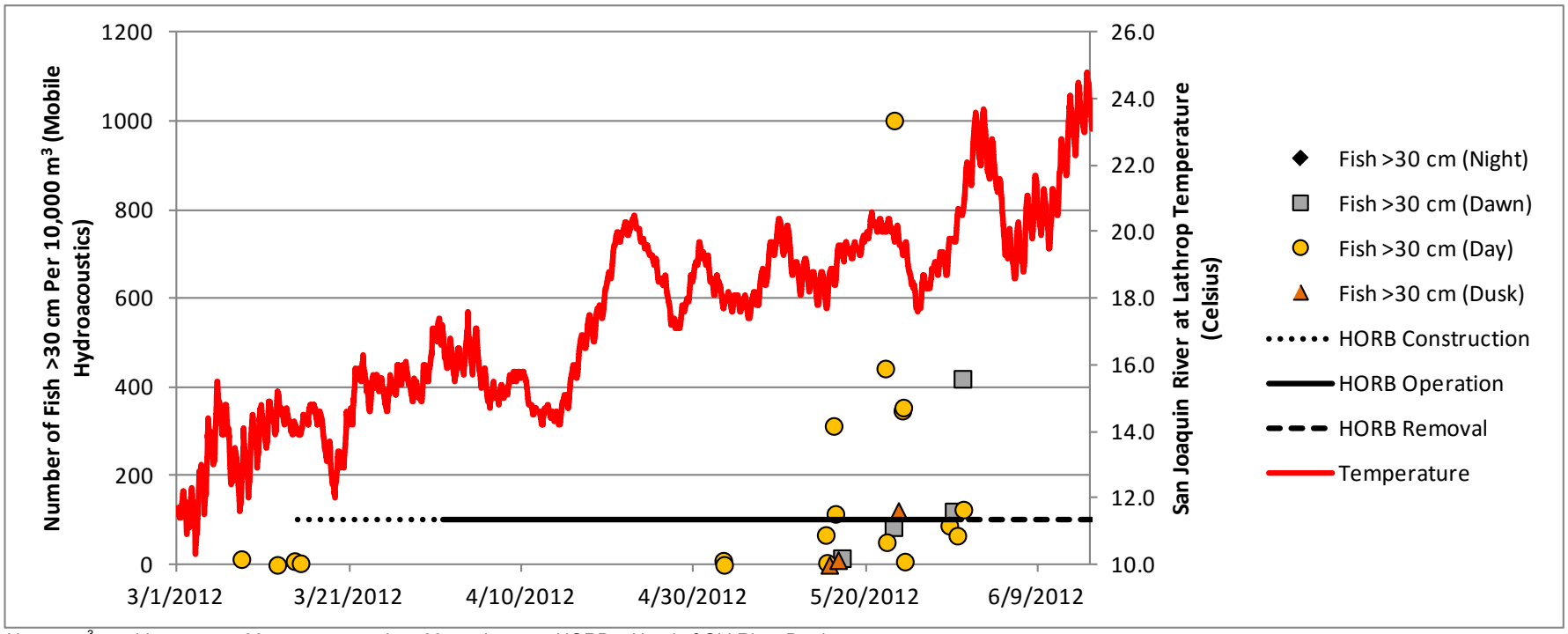


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier

Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-5 **Estimated Large-Fish Density in Relation to River Discharge, Photoperiod, and Physical Barrier Status Observed During Down-Looking Mobile Hydroacoustic Surveys in 2012**

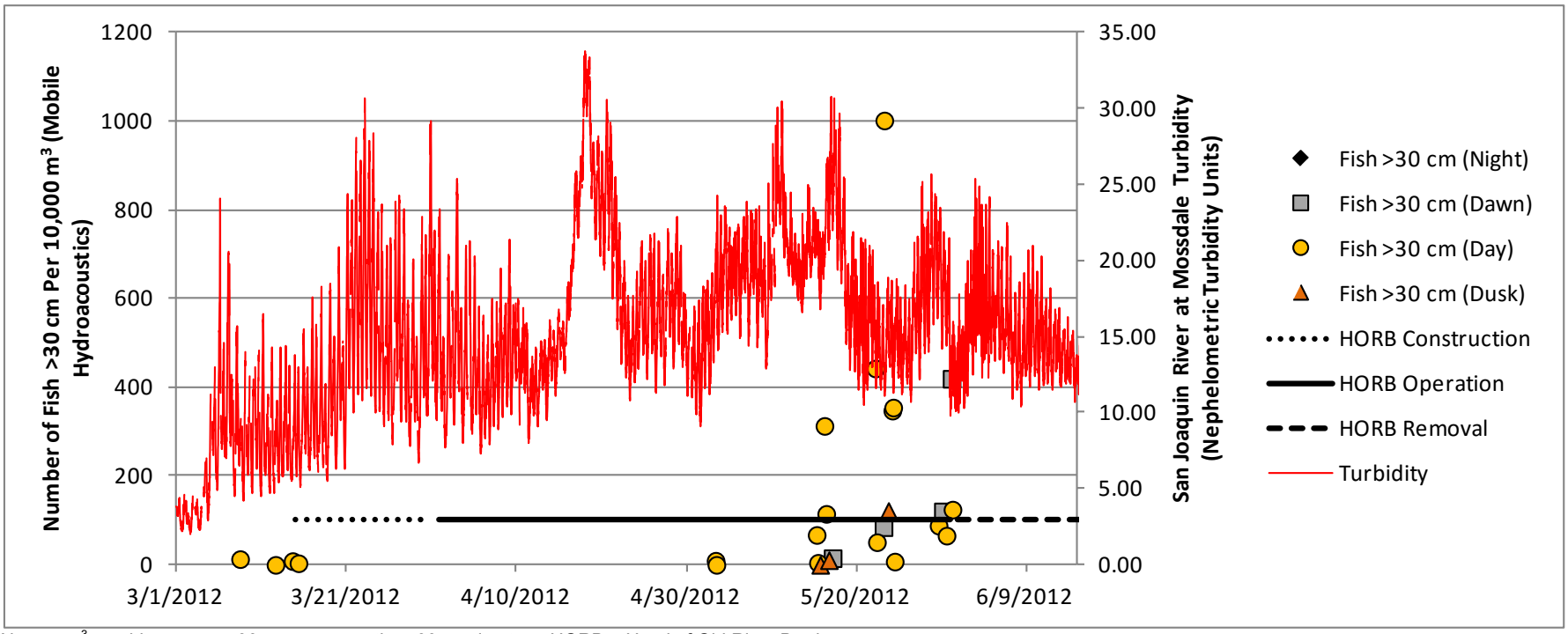


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier

Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-6 **Estimated Large-Fish Density in Relation to Water Temperature, Photoperiod, and Physical Barrier Status Observed During Down-Looking Mobile Hydroacoustic Surveys in 2012**

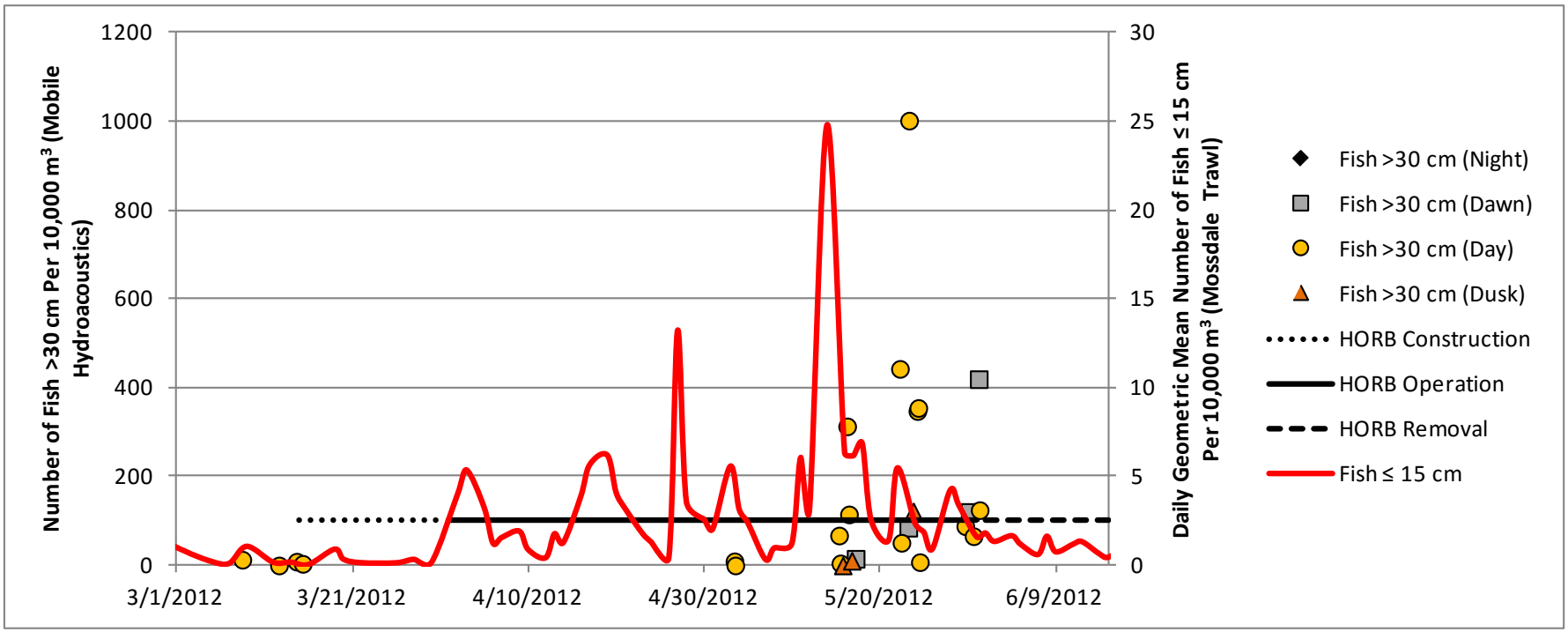


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier

Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-7 **Estimated Large-Fish Density in Relation to Turbidity, Photoperiod, and Physical Barrier Status Observed During Down-Looking Mobile Hydroacoustic Surveys in 2012**

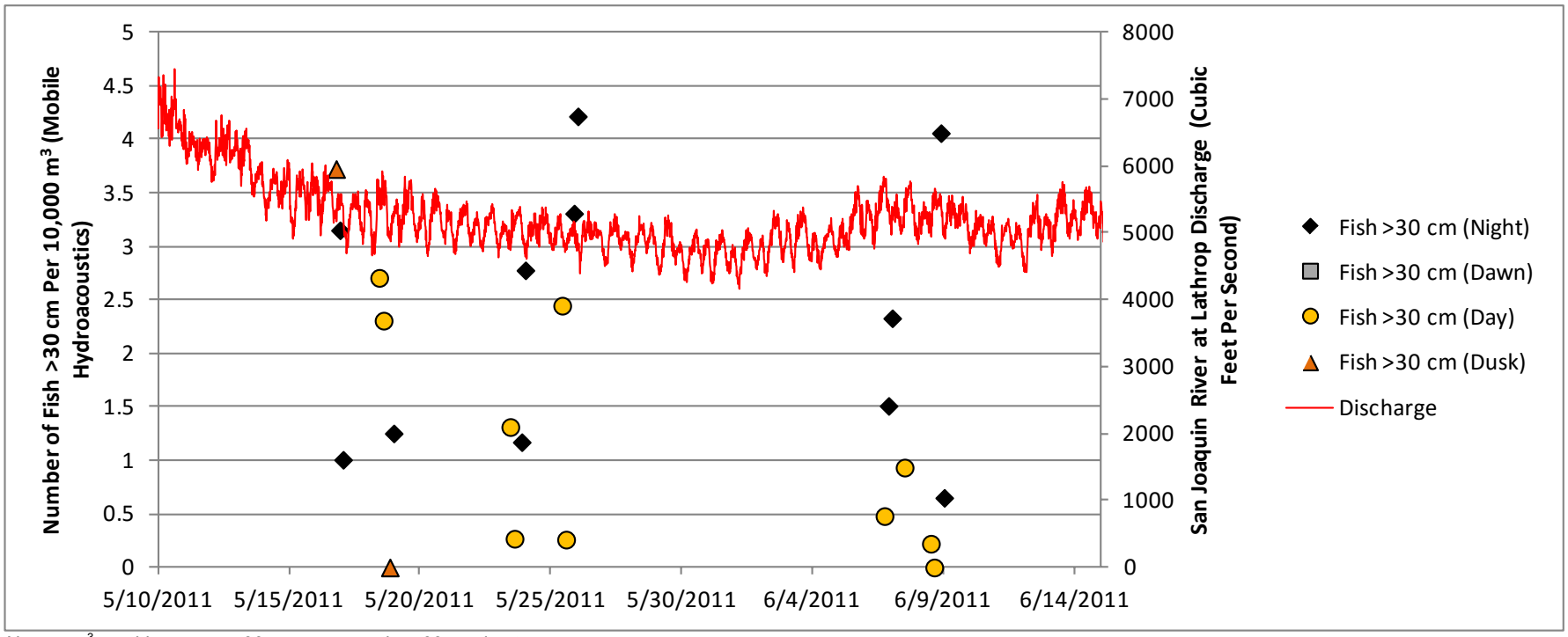


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier; ≤15 cm = less than or equal to 15 centimeters

Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

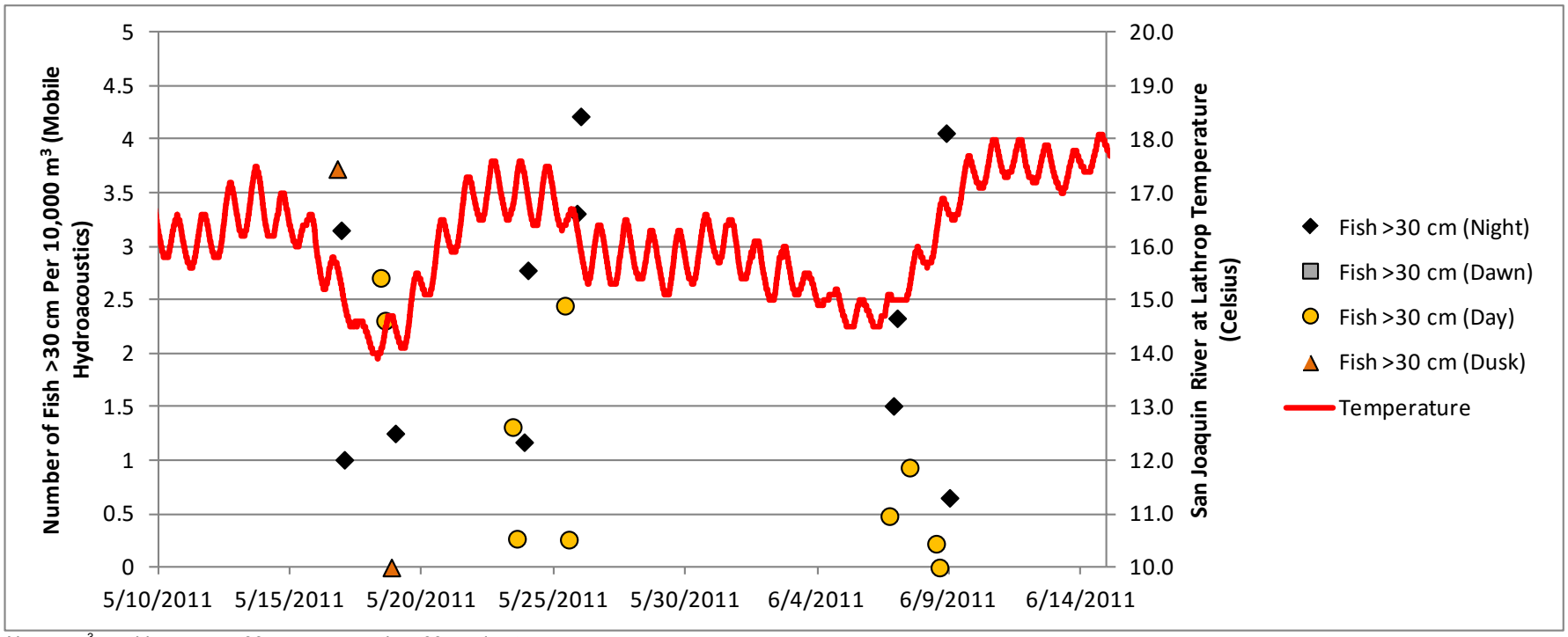
Figure G-8 **Estimated Large-Fish Density in Relation to Smaller-Fish Density, Photoperiod, and Physical Barrier Status Observed During Down-Looking Mobile Hydroacoustic Surveys in 2012**



Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters

Source Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

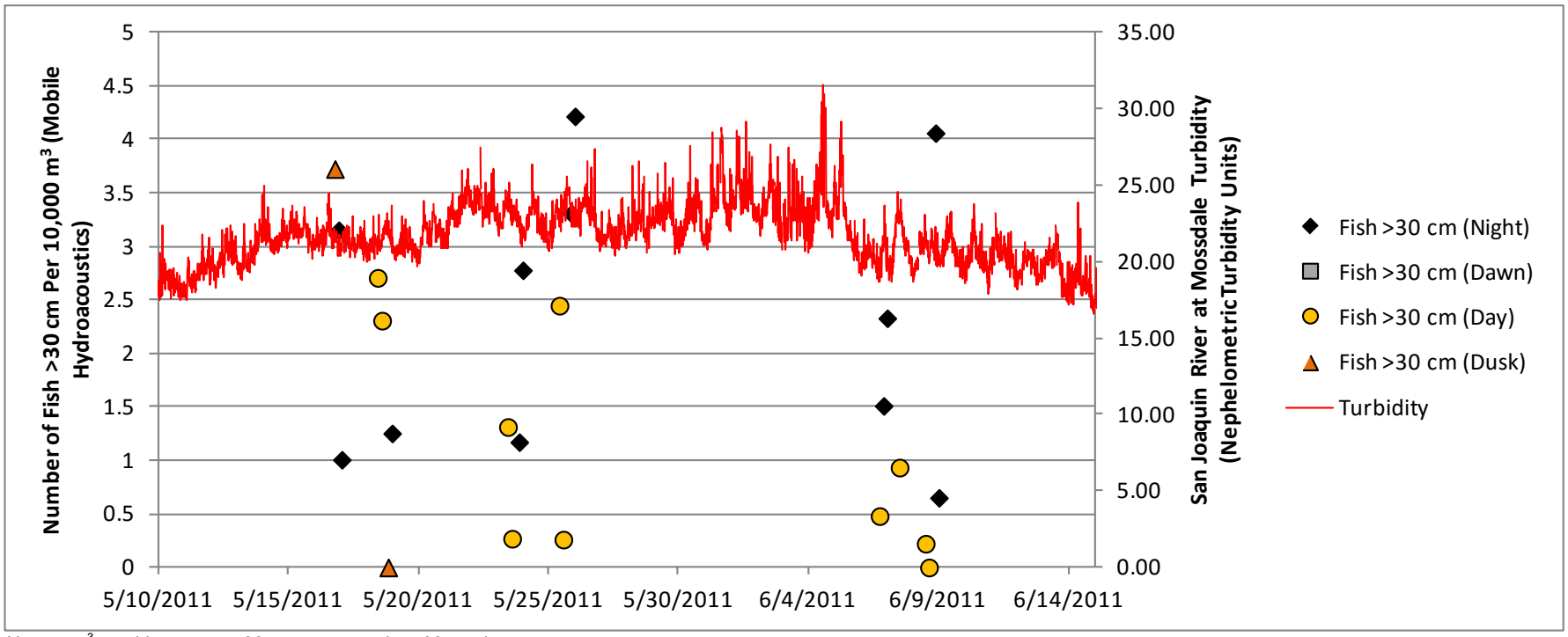
Figure G-9 **Estimated Large-Fish Density in Relation to River Discharge and Photoperiod Observed During Side-Looking Mobile Hydroacoustic Surveys in 2011**



Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-10 **Estimated Large-Fish Density in Relation to Water Temperature and Photoperiod Observed During Side-Looking Mobile Hydroacoustic Surveys in 2011**

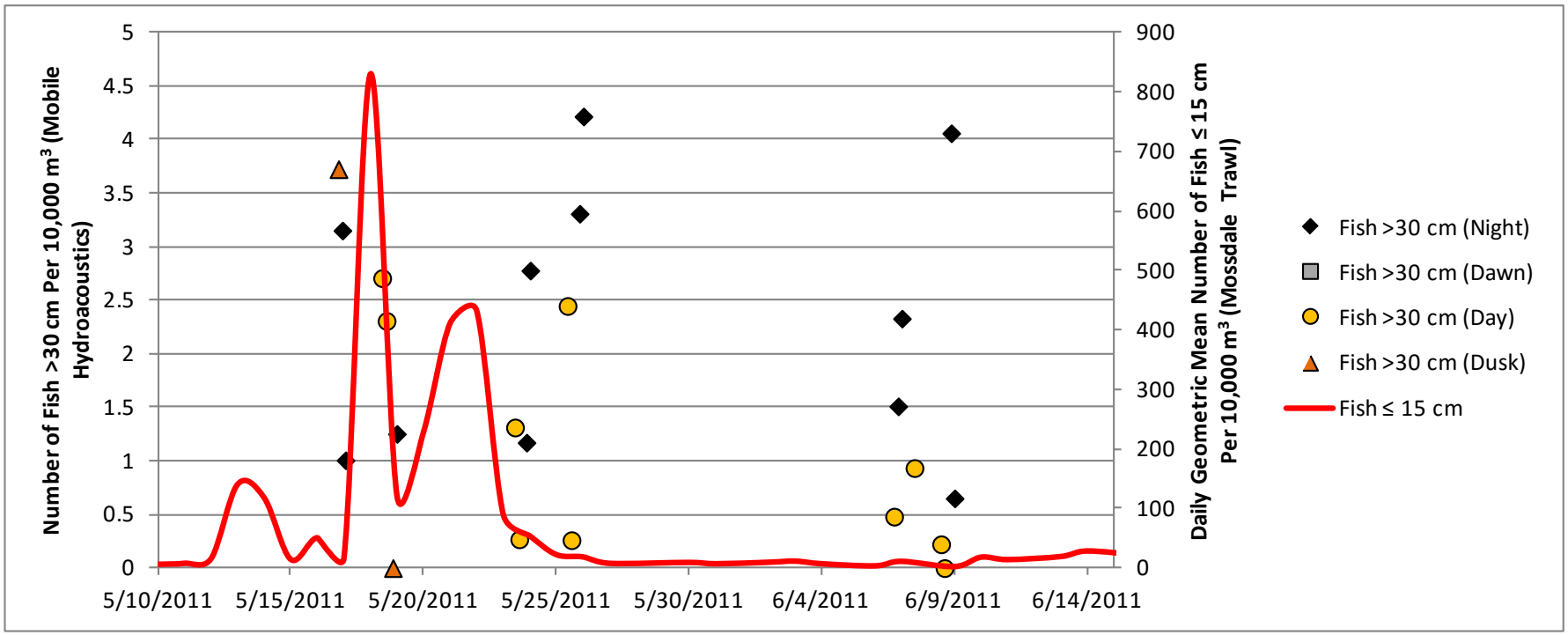


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-11

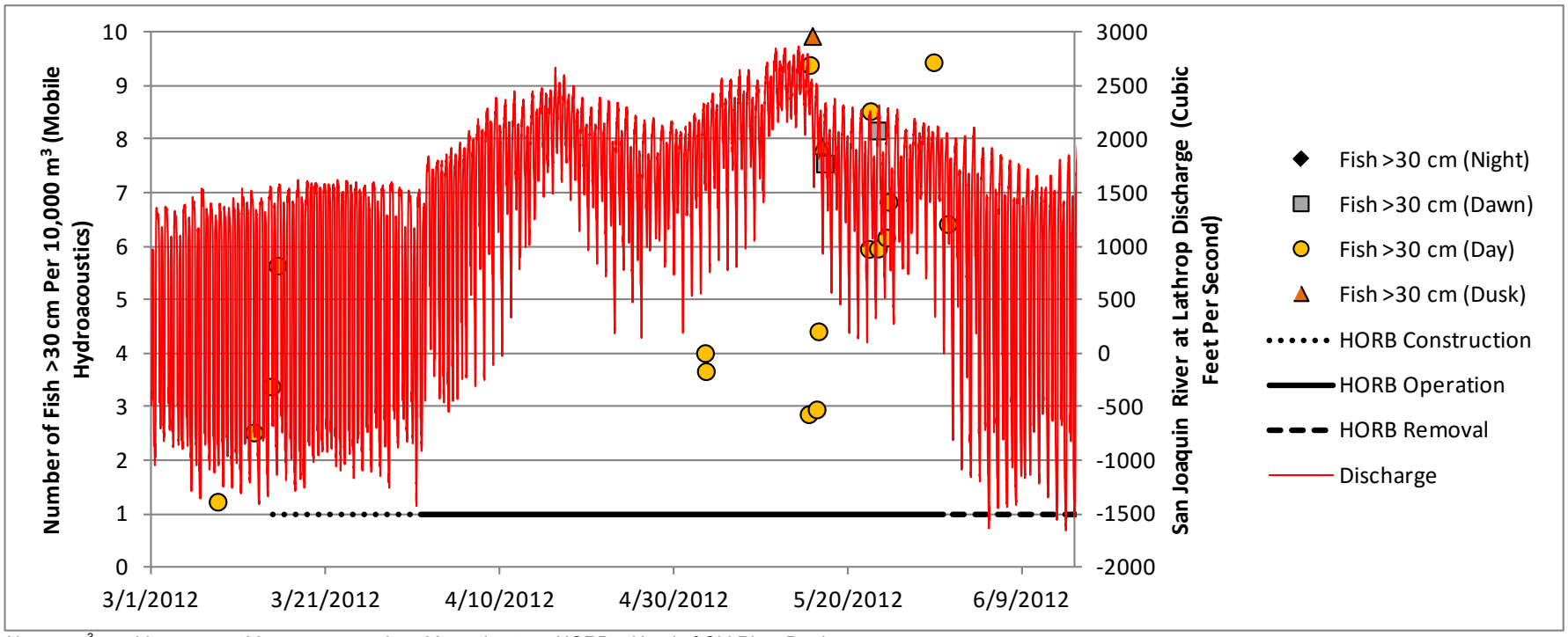
Estimated Large-Fish Density in Relation to Turbidity and Photoperiod Observed During Side-Looking Mobile Hydroacoustic Surveys in 2011



Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; ≤15 cm = less than or equal to 15 centimeters

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-12 **Estimated Large-Fish Density in Relation to Smaller-Fish Density and Photoperiod Observed During Side-Looking Mobile Hydroacoustic Surveys in 2011**

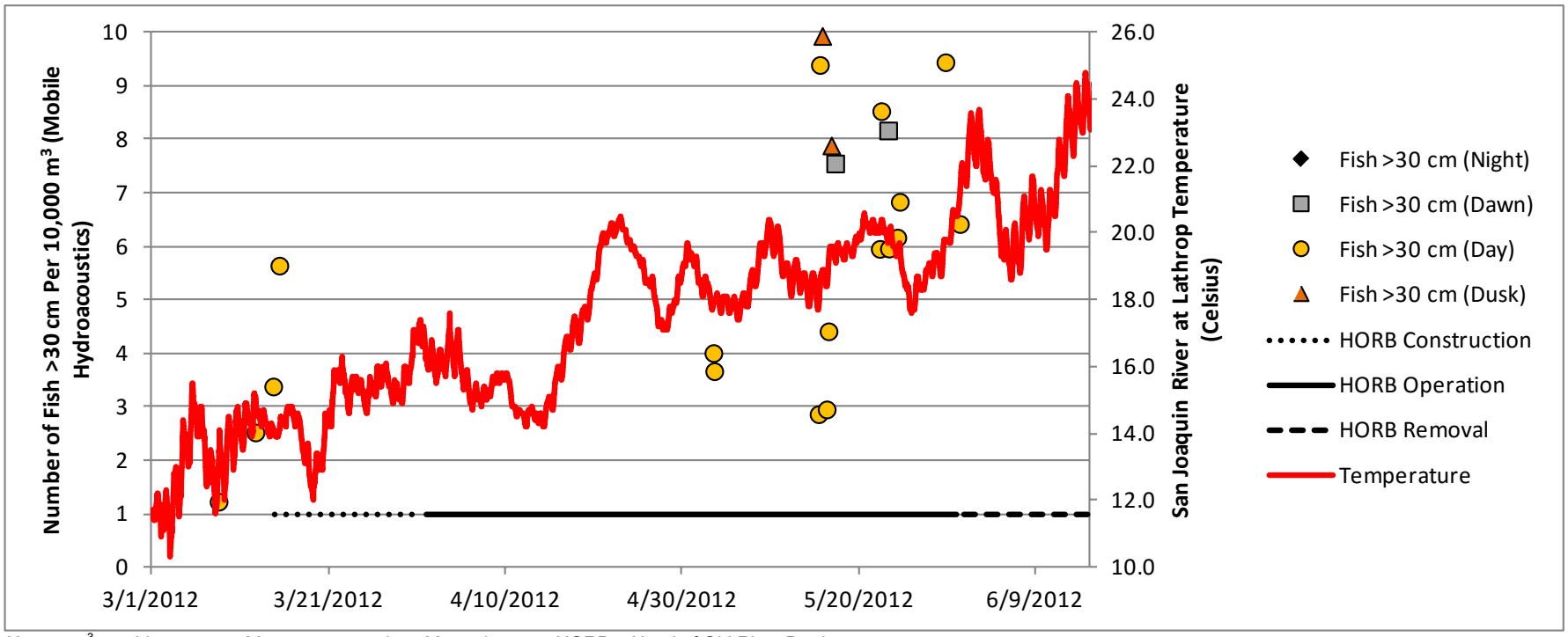


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier

Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-13 **Estimated Large-Fish Density in Relation to River Discharge, Photoperiod, and Physical Barrier Status Observed During Side-Looking Mobile Hydroacoustic Surveys in 2012**

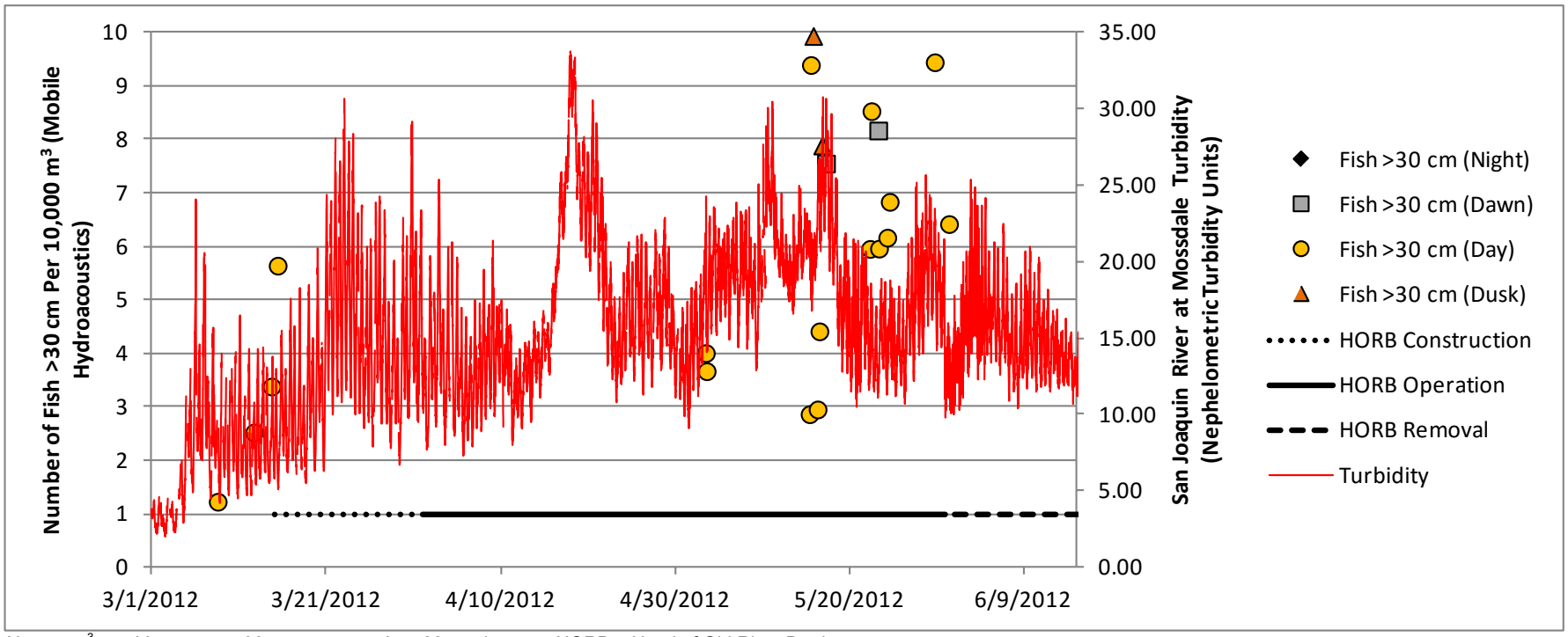


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier

Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-14 **Estimated Large-Fish Density in Relation to Water Temperature, Photoperiod, and Physical Barrier Status Observed During Side-Looking Mobile Hydroacoustic Surveys in 2012**

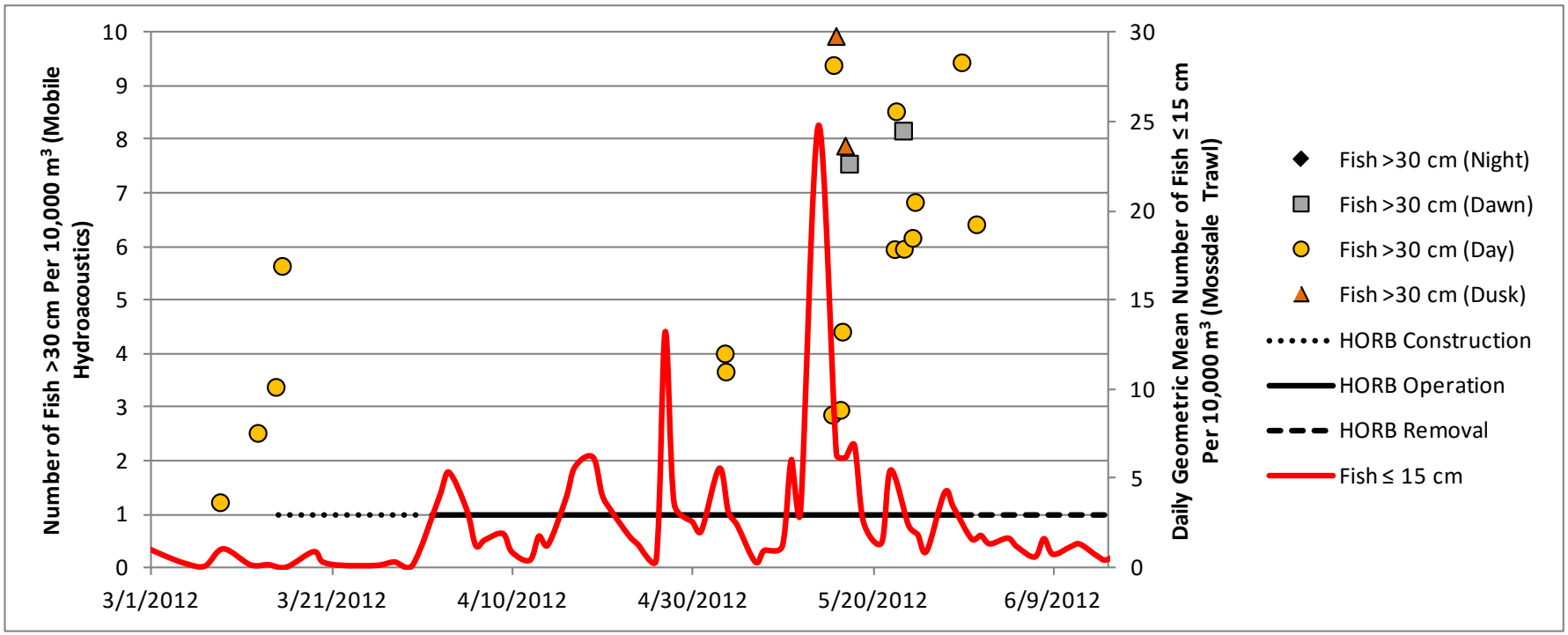


Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier

Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period

Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-15 **Estimated Large-Fish Density in Relation to Turbidity, Photoperiod, and Physical Barrier Status Observed During Side-Looking Mobile Hydroacoustic Surveys in 2012**



Notes: m^3 = cubic meters; >30 cm = greater than 30 centimeters; HORB = Head of Old River Barrier; ≤15 cm = less than or equal to 15 centimeters
Horizontal black line indicates Head of Old River physical rock barrier construction, operation, and removal period
Sources: Present study (hydroacoustic data) and Baldwin, pers. comm., 2013; Dempsey, pers. comm., 2013 (California Data Exchange Center data)

Figure G-16 **Estimated Large-Fish Density in Relation to Smaller-Fish Density, Photoperiod, and Physical Barrier Status Observed During Side-Looking Mobile Hydroacoustic Surveys in 2012**

APPENDIX H

Illustrative Example of Striped Bass Predation Using Bioenergetics Modeling

H.1 METHODS

Bioenergetics modeling was used to provide perspective on an estimated potential fish consumption by predatory fishes at the Head of Old River (HOR) study area in relation to densities of prey fish in the local area. Similar methods were used by Miranda et al. (2010) to estimate the potential for consumption by predatory fish at the fish salvage facilities (Byron, California) release sites. The analysis focused on striped bass (*Morone saxatilis*) because angling catch rates at the HOR study area suggest that this species may be the most common of the four focal fish species during this study period. In addition, bioenergetics modeling parameters have been developed for this species in the San Francisco Bay/Sacramento–San Joaquin Delta (Loboschefsky et al. 2012) and not for any of the other focal fish species.

The bioenergetics modeling was conducted using the software Fish Bioenergetics 3.0 (Hanson et al. 1997). This software estimates the food requirements of predatory fish given their energy requirements for growth, metabolism, and other processes. The main model inputs for predatory fish include an estimate of growth (start and end mass over a certain period) and energy density. The main inputs for predator food include the percentage of diet biomass made up by fish and other sources, and the energy density of the dietary items. The main environmental input affecting metabolism is water temperature. The model as implemented for the present study did not segregate by sex, or address bimaturation or ocean emigration as factors. As described herein, the model used for the present study essentially assumed that the density of striped bass occurring at the HOR study area during the study period remained constant (although the same individuals were not necessarily present all the time).

The first stage of the modeling was to develop start and end predator mass during the period of interest, which was taken over a 61-day spring period from April 1 through May 31. The striped bass bioenergetics model produced estimates of striped bass size at ages that can be used to provide an indication of growth rate for different sizes of fish (Loboschefsky, pers. comm., 2013) (Table H-1). The difference in average striped bass fork length (FL) between summer and fall was expressed as a daily percentage change in length from the starting length in spring (Figure H-1).

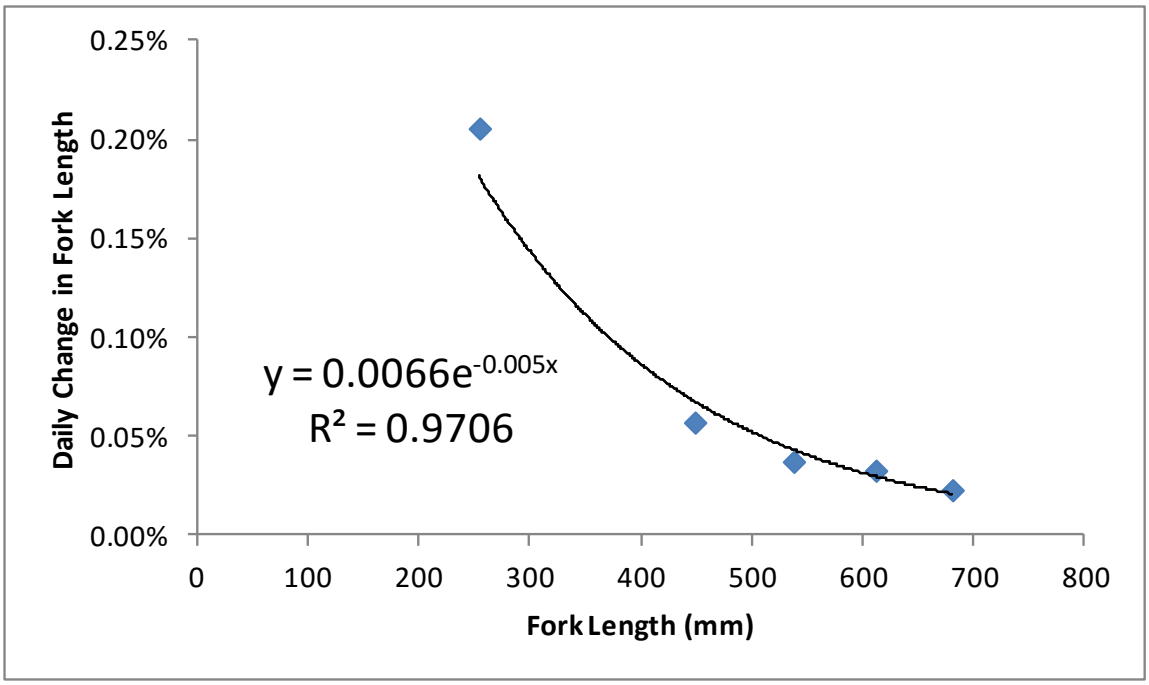
Table H-1
Estimated Seasonal Fork Length (mm) of Striped Bass from Bioenergetics Modeling[1]

Age	Spring	Summer	Fall	Winter
1	172	188	204	220
2	254	301	353	412
3	448	471	493	516
4	537	555	573	592
5	611	629	646	664
6	680	694	709	723

Note: mm = millimeters

[1] Males and females combined. Striped bass exhibit bimaturation with males maturing at age 2 and females between ages 4 and 6.

Source: Loboschefsky, pers. comm., 2013



Note: mm = millimeters

Source: Present study, based on data from Loboschefsky, pers. comm., 2013

Figure H-1 Daily Percentage Change in Striped-Bass Fork Length Assumed in Bioenergetics Modeling

From this point forward, fork length is expressed in centimeters (cm) instead of millimeters (mm). This relationship was used to estimate start and end mass for striped bass at the midpoint of size classes from 30 to 35 cm total length (TL) to 100 to 105 cm TL (applying a conversion from TL to FL from FishBase.org [FL = TL/1.072961; Froese and Pauly 2011] and a conversion from FL to mass [0.0066*(FL in mm) 3.12; Kimmerer et al. 2005]) (Table H-2). Applying this procedure to larger sizes of striped bass involves extrapolation beyond the range of the seasonal fork length show in in Table H-1. Striped bass energy density was assumed to be 6,488 Joules per gram (J/g) across all size classes (Hanson et al. 1997: A-5).

Striped bass diet composition was based on interpolation of values used by Loboschefsky et al. (2012), wherein 0.82 of the diet biomass for age 2 striped bass (25.4 cm FL in spring) was fish and 0.99 of the biomass for age 3 striped bass (44.8 cm FL in spring) was fish (Table H-3). Fish prey energy density was assumed to be 4,800 J/g (Loboschefsky et al. 2012), and the remainder of the diet was assumed to have an energy density of 3,000 J/g, similar to other potential striped bass prey shown by Loboschefsky et al. (2012).

The detailed model parameters and equations used in the bioenergetics modeling are presented by Hanson et al. (1997: A-5) and summarized in Table H-4. Two sets of parameters were used, one for 32.5-cm to 47.5-cm fish, and another for fish 52.5 cm and greater, based on the transition of males to adulthood. As previously noted, the model did not account for potential differences between male and female striped bass as they were not treated separately, and there was no accounting for energy expended for reproductive purposes.

Table H-2
Assumed Start/End Mass of Striped Bass at the Midpoint of Size Classes from 30–35 cm Total Length to 100–105 cm Total Length

Start TL (cm)	Start FL (cm)	Start Mass (g)	Daily Growth (%)	Growth from April 1 to May 31 (cm)	Final FL (cm)	Final Mass (g)
32.5	30.3	364.1	0.15	2.7	33.0	474.4
37.5	35.0	569.0	0.11	2.5	37.4	703.0
42.5	39.6	840.8	0.09	2.2	41.8	995.3
47.5	44.3	1,189.6	0.07	1.9	46.2	1,360.7
52.5	48.9	1,625.6	0.06	1.7	50.6	1,809.1
57.5	53.6	2,159.2	0.05	1.5	55.1	2,350.7
62.5	58.3	2,800.7	0.04	1.3	59.5	2,996.3
67.5	62.9	3,560.8	0.03	1.1	64.0	3,756.9
72.5	67.6	4,450.2	0.02	0.9	68.5	4,643.6
77.5	72.2	5,479.5	0.02	0.8	73.0	5,667.6
82.5	76.9	6,659.8	0.01	0.7	77.6	6,840.4
87.5	81.6	8,001.8	0.01	0.6	82.1	8,173.4
92.5	86.2	9,516.7	0.01	0.5	86.7	9,678.1
97.5	90.9	11,215.4	0.01	0.4	91.3	11,366.0
102.5	95.5	13,109.3	0.01	0.3	95.9	13,248.6

Notes: cm = centimeters; FL = fork length; g = grams; TL = total length
Source: Present study, based on data from Loboschefsky, pers. comm., 2013

Table H-3
Assumed Proportional Biomass of Fish in Striped Bass Diet at the Midpoint of Size Classes from 30 to 35 cm Total Length to 100 to 105 cm Total Length

Start TL (cm)	Fish as Proportion of Diet Biomass
32.5	0.862851
37.5	0.903686
42.5	0.944521
47.5	0.985356
52.5	0.99
57.5	0.99
62.5	0.99
67.5	0.99
72.5	0.99
77.5	0.99
82.5	0.99
87.5	0.99
92.5	0.99
97.5	0.99
102.5	0.99

Notes: cm = centimeters; TL = total length
Source: Present study, based on data from Loboschefsky et al. 2012

Table H-4
Parameter Values Used in Striped Bass Bioenergetics Modeling

Variables	32.5 to 47.5 cm TL	52.5 to 102.5 cm TL
Consumption Variables		
CA (mass-dependence function intercept, 1-gram fish at optimum water temperature)	0.302	0.302
CB (mass-dependence coefficient)	-0.252	-0.252
CK1 (temperature-dependence fraction of maximum rate, increasing portion of curve)	0.255	0.323
CK4 (temperature-dependence fraction of maximum rate, decreasing portion of curve)	0.9	0.85
CQ (lower water temperature at which temperature dependence is a small fraction [CK1] of maximum rate)	6.6	7.4
CTL (water temperature at which temperature dependence is reduced fraction [CK4] of maximum rate, increasing portion of curve)	32	30
CTM (water temperature [≥CTO] at which dependence is still 0.98 of the maximum rate, decreasing portion of curve)	29	28
CTO (water temperature at which dependence is 0.98 of the maximum rate, increasing portion of curve)	18	15
Equation	3	3
Egestion & Excretion Variables		
Equation	1	1
FA (constant proportion of consumption)	0.104	0.104
UA (constant proportion of assimilated energy [consumption minus egestion])	0.068	0.068
Respiration Variables		
ACT (activity multiplier)	1	1
BACT (water temperature dependence coefficient of swimming speed at water temperatures below RTL)	0	0
Equation	1	1
RA (specific weight of oxygen consumed by a 1-gram fish at 0°C and zero swimming speed)	0.003	0.003
RB (slope of the allometric mass function for standard metabolism)	-0.218	-0.218
RK1 (intercept for swimming speed above cutoff temperature)	1	1
RK4 (mass dependence coefficient for swimming speed at all temperatures)	0	0
RQ (rate at which the function increases over relatively low water temperatures)	0.076	0.076
RTL (cutoff temperature at which the activity relationship changes)	0	0
RTM (maximum lethal temperature, but set to zero)	0	0
RTO (coefficient for swimming speed dependence on metabolism)	0.5	0.5
SDA (specific dynamic action, i.e., the proportion of assimilated energy lost to the cost of assimilating foodstuffs, especially proteins)	0.172	0.172

Notes: cm = centimeters; TL = total length
Source: Hanson et al. 1997: A5

Mean daily water temperature data from April 1 through May 31 in 2011 and 2012 for the San Joaquin River at Lathrop (SJL) station were used for input to the bioenergetics modeling.

The bioenergetics modeling provided the estimated total fish prey biomass consumption from April 1 through May 31 by a single striped bass within each of the size classes from 30-35-cm TL to 100-105-cm TL, from which a mean daily fish biomass consumption of each size class was derived. This size range covers most of the striped bass typically collected with fyke traps on the Sacramento River (DuBois et al. 2012).

An illustrative example of potential consumption at the HOR study area was provided using the consumption estimates derived from bioenergetics modeling. This example has appreciable uncertainty, and is intended to illustrate the means by which consumption estimates can be derived using the results from bioenergetics modeling. The size composition of striped bass was estimated using size composition estimated from the mobile hydroacoustic surveys. The mean daily fish biomass consumed by a single striped bass was then calculated as the mean daily average consumption across all size classes, weighted by the proportion of all individuals in each size class. This mean consumption estimate for a single fish then was multiplied by the mean density of fish observed in the side-looking mobile hydroacoustics to give a mean daily consumption estimate per 10,000 cubic meters for the HOR study area, which then was converted to an estimate for the HOR study area based on the approximate volume of the HOR study area from bathymetry data.

The side-looking hydroacoustic data were used for density estimates because these data may more accurately reflect the pelagic distribution of striped bass, whereas the down-looking hydroacoustic data may include demersal species such as common carp (which were abundant in visual observations made near the 2012 Head of Old River Barrier [HORB]). The density specific consumption estimates were used to illustrate the potential consumption of fish prey in relation to prey fish biomass density entering the HOR study area.

Note that the bioenergetics modeling described here assumes a static size composition and density of striped bass at the HOR study area, but makes no assumptions about the length of time that striped bass may spend at the site. Residence times for striped bass at the HOR study area tends to be quite short (see Section 6.3.1, "Data from Acoustically Tagged Predatory Fish"), but the modeling implicitly assumes replacement of emigrating individuals by the same density of immigrating individuals. Prey biomass was estimated from the Mossdale trawl data, with a particular focus on juvenile Chinook salmon, by converting fork length to biomass using equations from Kimmerer et al. (2005) and Froese and Pauly (2011).

Fish growth rates may be higher than the "average" rates assumed herein if more efficient prey capture is facilitated by habitat conditions (e.g., at water diversion structures; see Vogel 2011: Figure 42). In addition, neither the identity of predatory fish from echoes nor the extent to which small-fish density at Mossdale represents small-fish density at the HOR study area are known. As described later herein, the illustrative example of consumption at the HOR study area makes numerous assumptions; these assumptions generally include considerable uncertainty. Nevertheless, the illustrative example serves to provide some speculation on the estimated potential consumption rate, which then provides context for additional estimates of predation on acoustically tagged juvenile salmonid by striped bass.

H.2 RESULTS

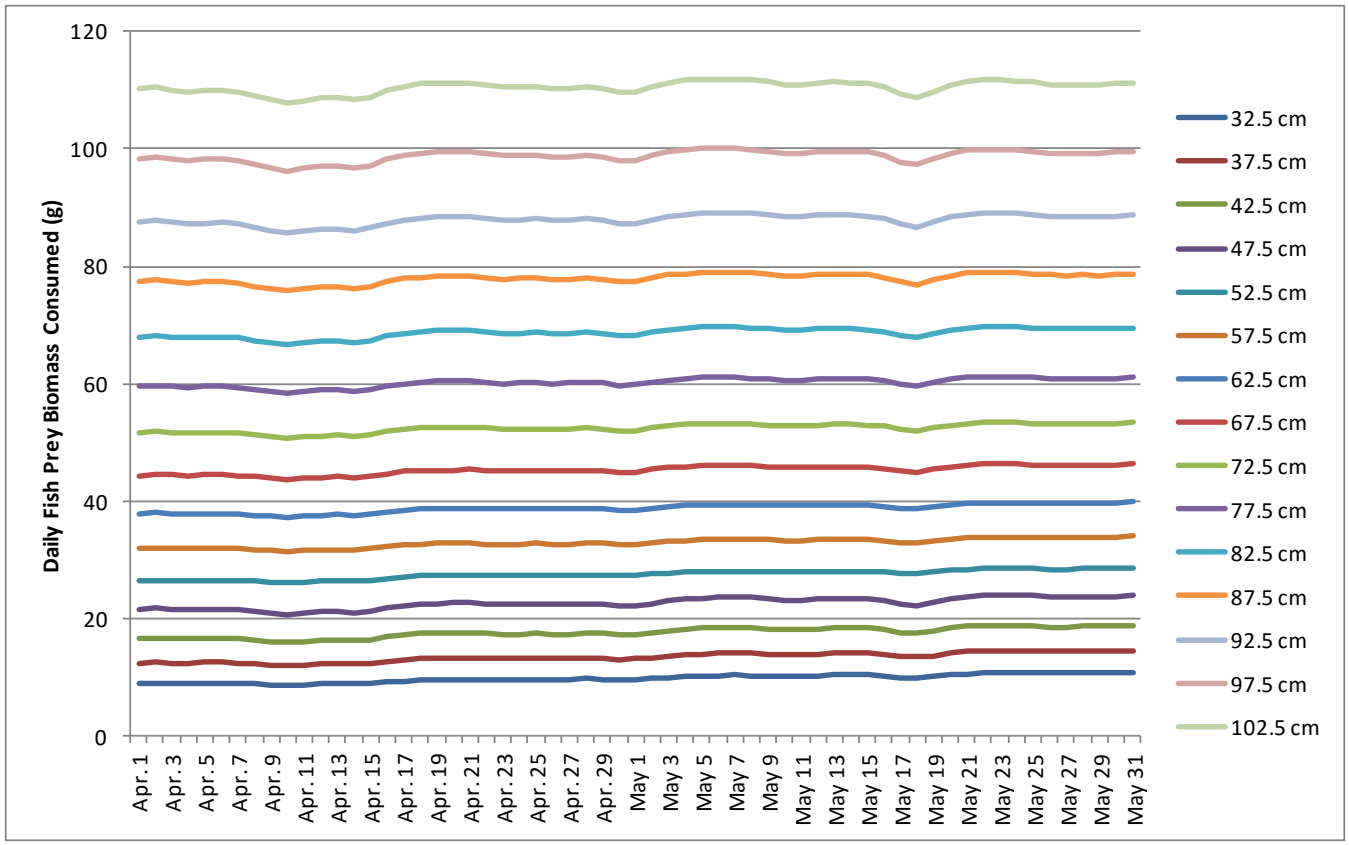
H.2.1 STRIPED BASS FISH PREY CONSUMPTION RATES

Bioenergetics modeling of potential consumption of fish prey by striped bass estimated that a 32.5-cm TL striped bass growing at an average rate and experiencing the 2011 water temperatures found near the HOR study area (San Joaquin River near Lathrop) would consume an average of approximately 9.8 grams of fish prey per day from April 1 to May 31 (Table H-5; Figure H-2). The daily consumption by the largest size of striped bass considered (102.5 cm) for the same water temperature was estimated to be 110.5 grams. To provide some perspective to these results, application of the length/weight relationship from Kimmerer et al. (2005) suggests that a 50-mm FL juvenile Chinook salmon weighs approximately 1.3 grams and a 100-mm FL juvenile Chinook salmon weighs approximately 13.7 grams. Thus, for example, a 62.5-cm striped bass might consume around three 100-mm juvenile Chinook salmon per day to satisfy its bioenergetics requirements (i.e., juveniles similar in size to the experimental fish used in the present study), based on the modeling results.

Table H-5
Estimated Mean Daily Fish Prey Consumption from April 1 through May 31 by Striped Bass Ranging in Total Length from 32.5 cm to 102.5 cm for Water Temperatures Recorded at the San Joaquin River near Lathrop in 2011 and 2012

Length (cm)	Mean Daily Fish Prey Consumption (grams)	
	2011	2012
32.5	9.77	11.10
37.5	13.38	15.27
42.5	17.59	20.17
47.5	22.58	26.01
52.5	27.47	31.80
57.5	32.84	38.17
62.5	38.76	45.22
67.5	45.26	52.98
72.5	52.38	61.51
77.5	60.16	70.85
82.5	68.66	81.04
87.5	77.90	92.13
92.5	87.93	104.17
97.5	98.78	117.20
102.5	110.48	131.24

Note: cm = centimeters
Source: Present study

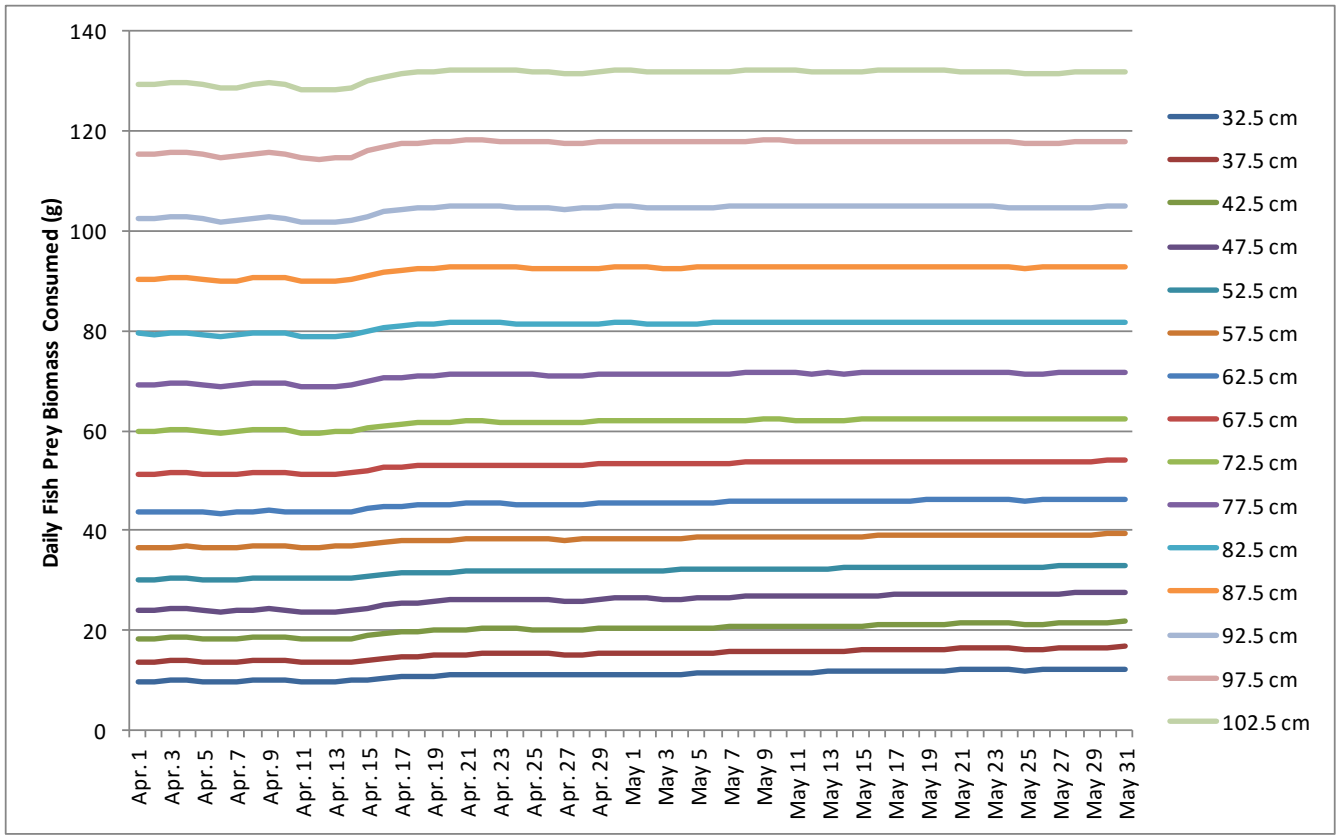


Notes: g = gram; cm = centimeter; TL = total length

Source: Present study

Figure H-2 **Estimated Daily Biomass of Fish Prey Consumed by Striped Bass of 32.5 cm to 102.5 cm TL from April 1–May 31, Based on 2011 Water Temperature Data at the Head of Old River**

Water temperature for April 1 through May 31, 2012, averaged 18.0 degrees Celsius (°C) (range: 14.5 to 21.3°C), which was higher than in 2011 (mean 15.8°C, range: 14.0 to 18.1°C). Assuming the same growth rate of striped bass in both years, water temperature effects on metabolism may have led to greater prey consumption requirements for 2012 than in 2011 (Table H-5; Figures H-2 and H-3). The mean daily fish prey consumption rate was estimated to be 13.7% greater in 2012 than in 2011 for a 32.5-cm striped bass, and the difference between years increased with increasing fish size, so that the mean daily fish prey consumption rate of a 102.5-cm striped bass was estimated to be 18.8% greater in 2012 than in 2011.



Notes: g = gram; cm = centimeter; TL = total length

Source: Present study

Figure H-3 **Estimated Daily Biomass of Fish Prey Consumed by Striped Bass of 32.5 cm to 102.5 cm TL from April 1–May 31, Based on 2012 Water Temperature Data at the Head of Old River**

H.2.2 ILLUSTRATIVE EXAMPLE BASED UPON ASSUMPTIONS

An illustration of the possible calculations that can be made using the results (from Section H.2.1, "Striped Bass Fish Prey Consumption Rates") is provided here for consumption of prey fish at the HOR study area by striped bass. The calculations are illustrative estimates and not meant to represent actual consumption rates due to the high uncertainties associated with the estimates. As noted in Section H.1, "Methods," it was assumed that the side-looking mobile hydroacoustic data provides an estimate of striped bass density and size distribution at the HOR study area. The size distribution of fish greater than 30 cm TL based on fish echoes detected is shown in Table H-6; fish larger than 105 cm were excluded because it is uncertain whether they would represent striped bass or other fish species. (Targets as large as approximately 425 cm were detected by side-looking surveys in 2012.)

Assuming that this is a reasonable size distribution for striped bass capable of preying on juvenile Chinook salmon, the weighted mean daily consumption of fish prey per striped bass can be worked out by combining the mean daily prey fish consumption (Table H-5) with the size composition (Table H-6). This gives estimates of daily mean fish prey biomass consumed per striped bass of 20.9 grams in 2011 and 29.9 grams in 2012. The mean density of large fish greater than 30 cm TL from the mobile hydroacoustic surveys in May and June 2011 was 1.7 fish per 10,000 cubic meters (m^3) (see Appendix G, Figure G-12). Assuming these fish were all striped

bass and had the size distribution shown in Table H-6, the daily consumption of prey fish in 2011 would be 36.6 grams per 10,000 m^3. The mean density of large fish greater than 30 cm TL from the mobile hydroacoustic surveys in May 2012 was 8.8 fish per 10,000 m^3 (see Appendix G, Figure G-16). Assuming these fish were all striped bass and had the size distribution shown in Table H-6, the daily consumption of prey fish in 2012 would be 264.5 grams per 10,000 m^3.

Table H-6
Size Frequency (Total Length, cm) of Fish Observed with Side-Looking Mobile Hydroacoustics

Length Class Midpoint (cm)	Percentage of Fish Observed	
	2011	2012
32.5	37	25
37.5	16	21
42.5	13	10
47.5	10	12
52.5	7	8
57.5	3	6
62.5	4	6
67.5	3	3
72.5	3	2
77.5	0	2
82.5	1	1
87.5	1	1
92.5	1	2
97.5	0	2
102.5	0	2

Notes: cm = centimeters
Fish greater than these sizes were excluded
Source: Present study

The estimates of daily consumption of prey fish for striped bass in the HOR study area can be compared to densities of small-bodied (less than 15 cm FL) prey fish from Mossdale trawling. Note again that the calculation is illustrative; factors such as gear efficiency of the trawl are unknown and likely affect prey species caught and their associated densities. The mean biomass density of prey fish for the period of May 16 through June 8, 2011, during which hydroacoustic surveys occurred (see Appendix G, Figure G-12) was 66.1 grams per 10,000 m^3. The mean biomass density of prey fish for the period of May 3 through May 31, 2012, during which mobile hydroacoustic surveys also occurred (see Appendix G, Figure G-16), was 20.3 grams per 10,000 m^3. The daily consumption rate for 2011 (36.6 grams per 10,000 m^3; see previous) was 55% of the prey fish biomass density. The daily consumption rate for 2012 (264.5 grams per 10,000 m^3; see previous) was greater than 1,300% of the prey fish biomass density.

Estimates of prey fish biomass density are significantly lower in relation to the potential daily consumption rate of striped bass. However, accounting needs to be made of the potential influx of prey fish into the area of the HOR study area. This can be done using estimates of discharge at Mossdale combined with prey fish biomass density.

Thus, assuming the prey-fish biomass density estimated from Mossdale trawling was moving downstream at a rate equivalent to discharge at Mossdale, an estimated mean 178.6 kg of prey fish entered the HOR study area each day during the period in 2011 noted previously, compared with 18.5 kg per day in 2012. As described in Section 2.2.3, "Local Fish Assemblage," an appreciable portion of the small-fish assemblage consisted of marked or unmarked juvenile Chinook salmon in these two years, as indicated by trawling at Mossdale.

The final piece of this illustrative example is to estimate daily consumption by striped bass by multiplying estimated daily consumption rate per 10,000 m^3 by the volume of the HOR study area. Bathymetric data were available for most zones of the study area, and to account for river stage, it was assumed that water depth was an additional 1 m on top of the mean absolute elevations of each zone. Thus, it was estimated that the HOR study area had a volume of 63,257 m^3 (including only zones 1 through 64, to account for the 2012 HORB). The resulting daily estimates of all prey fish consumption by striped bass were 0.231 kg per day in 2011 and 1.67 kg per day in 2012. Based on the daily influx of prey fish estimated, this amounted to an estimated mean predation rate of 0.001 (0.13%) in 2011 and 0.09 (9.04%) in 2012. Repeating the calculations and only considering (unmarked) juvenile Chinook salmon prey biomass density, estimated predation rates were 0.0042 (0.42%) in 2011 and 0.174 (17.4%) in 2012.

In summary, the illustrative example provided (based upon the assumptions presented herein), indicates that the prey fish biomass density is significantly lower than the potential daily consumption rate capable by striped bass. The estimated mean predation rate of all prey fish consumed by striped bass ranged from less than 1% to 9% in 2011 and 2012, respectively. Similarly, predation by striped bass on unmarked juvenile Chinook salmon ranged from less than 1% to 17% in 2011 and 2012, respectively.

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APPENDIX I

Route Entrainment Analysis at Head of Old River, 2009 and 2010
(Reproduced from SJRGA 2013, Chapter 7)

CHAPTER 7

ROUTE ENTRAINMENT ANALYSIS AT HEAD OF OLD RIVER, 2009 AND 2010

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Methods

Supplementary analyses were conducted of the relationship between river conditions and the probability of remaining in the San Joaquin River at the head of Old River in 2009 and 2010. These analyses were based on the results of the data processing performed in the survival analysis of the 2009 and 2010 VAMP studies (SJRGA 2010, SJRGA 2011). Only detections classified as coming from live salmon smolts were used in this analysis. More information on data processing and the predator filter in the 2009 and 2010 studies is described in SJRGA, 2010 and SJRGA, 2011.

Analysis methods were the same as those used in the 2011 route entrainment analysis (Chapter 5). In addition to the covariates used in the 2011 route analysis, the status of the non-physical barrier at the head of Old River at the time of fish arrival at the barrier was included in the 2009 and 2010 analyses:

$$B_i = \begin{cases} 1, & \text{barrier open at arrival of tag } i \\ 0, & \text{barrier closed at arrival of tag } i \end{cases}$$

(data courtesy of the U. S. Bureau of Reclamation). Interaction effects between the barrier status and river flow, water velocity, and flow proportion were tested in the flow, velocity and flow proportion models, respectively.

Results

2009 Results

A total of 365 tags were observed passing the acoustic receivers in either the San Joaquin River or Old River near the head of Old River in 2009, with associated observations of river conditions. Of these 365 fish, 192 were observed entering Old River, while the other 173 remained in the San Joaquin River past the head of Old River. River flow and water velocity measured at the SJL gaging station in the San Joaquin River near Lathrop were very highly correlated in 2009 (r=0.99), with flow values ranging from -1,287 cfs to 2,133 cfs (average = 898 cfs) when tagged fish were passing the SJL gaging station and the OH1 gaging station in Old River just downstream of its divergence from the San Joaquin River. A description of the gaging station locations can be found in Chapter 4. Negative values of flow indicate reverse flow at the SJL gaging station. At the OH1 gaging station, flow and water velocity were also highly correlated (r=0.96), with flow values ranging from 203 cfs to 2,186 cfs (average = 1,515 cfs) when tagged fish passed the SJL and OH1 gaging stations. No reverse flow was observed at the OH1 station. Flow at the SJL station was moderately negatively correlated with flow at the OH1 gaging station (r=-0.48). Water velocity measures from the two gaging stations were also moderately negatively correlated (r=-0.37). Water velocity at the SJL station ranged from -0.88 ft/s to 1.55 ft/s (average = 0.75 ft/s), while at the OH1 station, it ranged from 0.11 ft/s to 1.58 ft/s (average = 1.03 ft/s) while tagged fish passed the gaging stations. Flow proportion into the San Joaquin River was moderately correlated with flow into the San Joaquin River (r=0.57), with negative values of flow proportion corresponding to reverse flow at the SJL gage. Flow proportion into the San Joaquin River during the time of tagged fish passage of the gaging stations (pQ_{iA}) ranged from -722% to 91% (average = 10%), omitting one extreme negative value of -2,180%. The extreme negative values occurred when flow was reversed at the SJL gage and nearly the same magnitude as the positive flow at the OH1 gage. Because flow proportion was negative only under conditions of reverse flow, the reverse flow covariate (uQ_{iA}) was omitted from the multivariate analysis with the flow proportion model.

Results of the single-variate analyses relating route entrainment at the head of Old River to river conditions found significant effect of both flow and velocity at both the SJL and the OH1 gaging stations (P<0.0005 in each case, Table 7-1). Flow proportion into the San Joaquin River and the occurrence of reverse flow at the SJL gage were also significantly correlated with route entrainment (P<0.0001 in both cases), as was change in both velocity and flow at OH1 (P<0.0001 in both cases). The status of the non-physical barrier (on versus off) was significantly correlated with route entrainment (P=0.0010), as were exports at CVP (P=0.0010) and combined exports throughout the Delta (P=0.0040). However, exports at SWP alone were not significantly correlated with route entrainment at the head of Old River (P=0.2709). Fork length, release group, change in flow and velocity at SJL, and change in flow proportion into the San Joaquin were not significantly correlated with route entrainment, either (P>0.3 in each case; Table 7-1).

The single-variate analyses may suggest possible relationships, but due to confounding among the independent covariates and the possibility of a causal relationship with an unmonitored factor, it is not possible to conclude that changes in any of the significant single-variate measures directly produce changes in route entrainment at the head of Old River. Multi-variate analysis may shed more light on which covariates are worthy of further study, although causal relationships are still not discernible.

Multivariate analyses also found significant effects of flow and velocity at both the SJL and OH1 gaging stations, as well as flow proportion into the San Joaquin River, with significantly different effects when the non-physical barrier was on (barrier = 1) than when it was off

(barrier = 0) (Table 7-2). All three models (flow, velocity, and flow proportion) adequately fit the data (P>0.9), but the flow model accounted for more variation in route entrainment than either water velocity (ΔAIC=6.56) or flow proportion (ΔAIC=27.33) (Table 7-2). The flow model predicted the route entrainment probability according to:

$$\widehat{\psi}_A = \frac{exp(-1.20 + 0.002Q_A - 0.001Q_B)}{1 + exp(-1.20 + 0.002Q_A - 0.001Q_B)}$$

when the barrier was off, and

$$\widehat{\psi}_A = \frac{exp(-9.07 + 0.005Q_A + 0.002Q_B)}{1 + exp(-9.07 + 0.005Q_A + 0.002Q_B)}$$

when the barrier was on.

For flow at OH1 fixed at the mean observed value there when tagged fish were passing (1,515 cfs), increases in flow at SJL were predicted to increase the probability of a tagged fish remaining in the San Joaquin River, with a steeper increase if the barrier was on (Figure 7-1). For flow at SJL fixed at its mean observed value (893 cfs), increases in flow at OH1 were predicted to increase the probability of a tagged fish remaining in the San Joaquin River if the barrier was on, but were predicted to decrease the probability of remaining in the San Joaquin if the barrier was off (Figure 7-2).

2010 Results

A total of 430 tags were observed passing the acoustic receivers in either the San Joaquin River or Old River near the head of Old River in 2010, with associated observations of river conditions. Of these 430 tagged fish, 228 were observed entering Old River, while the other 202 fish remaining in the San Joaquin River past the head of Old River. River flow and water velocity measured at the SJL gaging station in the San Joaquin River at times when tagged fish were passing were highly correlated in 2010 (r=0.95). Observed flow values ranged from 909 cfs to 3,595 cfs (average = 2,595 cfs), and observed velocity values ranged from 0.5 ft/s to 2.3 ft/s (average = 1.6 ft/s). River flow and water velocity measured at the OH1 gaging station in Old River when tagged fish were passing were also highly correlated (r=0.92), with flow values ranging from 1,703 cfs to 3,404 cfs (average = 2,777 cfs) and velocity values ranging from 0.9 ft/s to 2.0 ft/s (average = 1.5 ft/s). There was little or no correlation between flow (r=0.04) or

Table 7-1
Results of Single-variate Analyses of Route Entrainment at the Head of Old River in 2009

Year	Covariate	F-test		
		F	df1, df2	P
2009	Velocity at SJL[a]	212.8572	1, 363	<0.0001
2009	Flow at SJL[a]	193.7478	1, 363	<0.0001
2009	Flow proportion into San Joaquin[a]	174.0139	1, 363	<0.0001
2009	Reverse flow into San Joaquin[a]	151.5927	1, 363	<0.0001
2009	Change in velocity at OH1[a]	40.8793	1, 347	<0.0001
2009	Flow at OH1[a]	22.6527	1, 363	<0.0001
2009	Change in flow at OH1[a]	16.8309	1, 347	<0.0001
2009	Velocity at OH1[a]	12.8934	1, 363	0.0004
2009	Barrier[a]	11.0410	1, 363	0.0010
2009	Exports at CVP[a]	10.9377	1, 363	0.0010
2009	Combined Exports[a]	8.3972	1, 363	0.0040
2009	Exports at SWP	1.2159	1, 363	0.2709
2009	Change in velocity at SJL	0.9906	1, 347	0.3203
2009	Fork Length	0.7137	1, 363	0.3988
2009	Release Group	0.8675	6, 358	0.5189
2009	Change in flow proportion into San Joaquin	0.3984	1, 347	0.5283
2009	Change in flow at SJL	0.0628	1, 347	0.8023

[a] Significant at 5% level

Figure 7-1
Fitted Probability of Remaining in the San Joaquin River at the Head of Old River versus River Discharge Measured at the SJL Gaging Station near Lathrop, CA, for River Discharge at OH1 Gaging Station in Old River Fixed at its Average (1,515 cfs), with 95% Confidence Bands, in 2009. Barrier is Non-Physical Barrier at Head of Old River

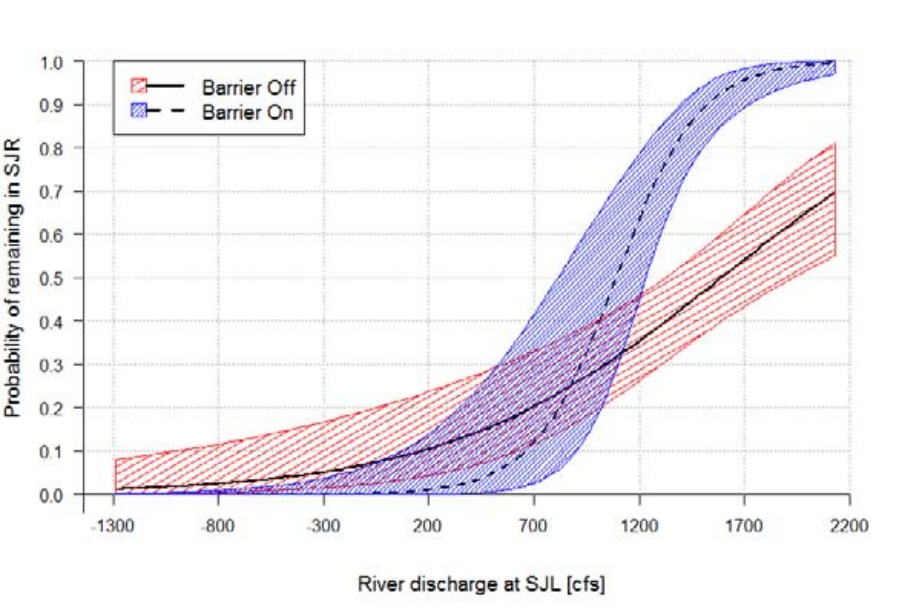


Figure 7-2
Fitted Probability of Remaining in the San Joaquin River at the Head of Old River versus River Discharge Measured at the OH1 Gaging Station in Old River, for River Discharge at SJL Gaging Station near Lathrop, CA, Fixed at its Average (893 cfs), with 95% Confidence Bands, in 2009. Barrier is Non-Physical Barrier at Head of Old River

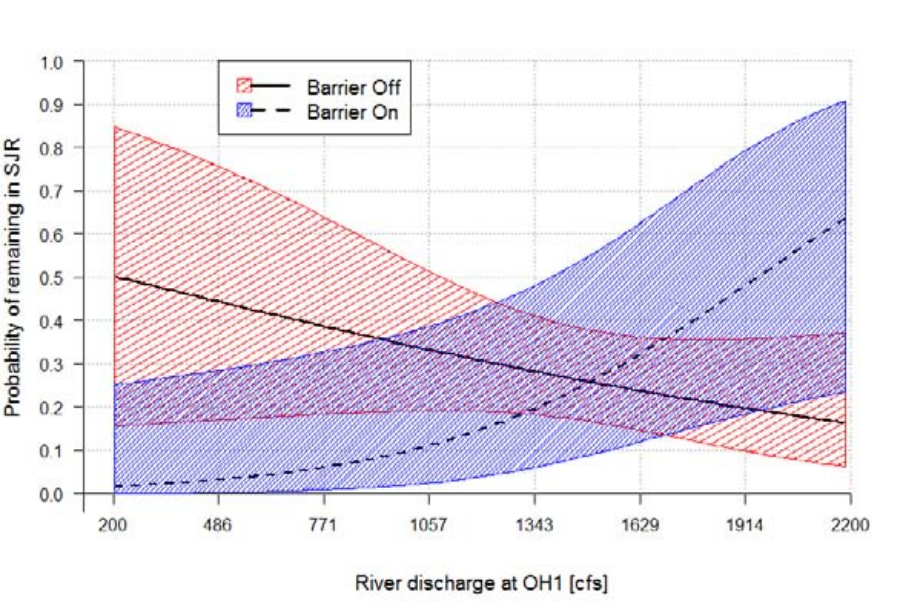


Table 7-2
Results of Multivariate Analyses of Route Entrainment at the Head of Old River in 2009

Model Type	Covariate[a]	Estimate	S.E.	t-Test		
				t	df	P
Flow	Intercept	-1.0723	0.2704	-3.966	359	<0.0001
	Q_A	1.6324	0.3647	4.476	359	<0.0001
	Q_B	-0.2749	0.209	-1.315	359	0.1893
	Barrier	0.0632	0.666	0.095	359	0.9244
	Q_A*Barrier	3.7580	1.2102	3.105	359	0.0021
	Q_B*Barrier	1.0539	0.3813	2.764	359	0.0060
	Goodness-of-fit: χ^2=2.5464, df=13, P=0.9991; AIC = 289.60					
Velocity	Intercept	-1.0640	0.2808	-3.776	360	0.0002
	V_A	1.7445	0.3938	4.430	360	<0.0001
	V_B	-0.3070	0.1728	-1.776	360	0.0766
	Barrier	-0.5429	0.8145	-0.667	360	0.5052
	V_A*Barrier	3.3994	1.2618	2.694	360	0.0074
	Goodness-of-fit: χ^2=2.9471, df=13, P=0.9981; AIC = 296.16					
Flow Proportion	Intercept	-1.8121	0.5039	-3.596	361	0.0004
	pQ_A	5.7413	1.4593	3.934	361	0.0001
	Barrier	-0.7723	1.3045	-0.592	361	0.5542
	pQ_A*Barrier	7.4123	4.2399	1.748	361	0.0813
	Goodness-of-fit: χ^2=6.3064, df=13, P=0.9343; AIC = 316.93					

[a] continuous covariates (Q_A, Q_B, V_A, V_B, pQ_A) are standardized

Table 7-3
Results of Single-variate Analyses of Route Entrainment at the Head of Old River in 2010

Year	Covariate	F-test		
		F	df1, df2	P
2009	Barrier[a]	14.4717	1, 428	0.0002
2009	Flow proportion into San Joaquin[a]	13.5411	1, 428	0.0003
2009	Flow at SJL[a]	9.0700	1, 428	0.0027
2009	Velocity at SJL[a]	7.1774	1, 428	0.0077
2009	Flow at OH1[a]	4.8240	1, 428	0.0286
2009	Change in velocity at OH1	3.1450	1, 413	0.0769
2009	Velocity at OH1	2.8854	1, 428	0.0901
2009	Combined Exports	1.3152	1, 428	0.2521
2009	Change in flow at OH1	1.2129	1, 413	0.2714
2009	Change in velocity at SJL	0.5482	1, 428	0.4595
2009	Fork Length	0.3062	1, 428	0.5803
2009	Release Group	0.7067	6, 423	0.6444
2009	Exports at SWP	0.0752	1, 428	0.7841
2009	Change in flow proportion into San Joaquin	0.0479	1, 413	0.8268
2009	Change in flow at SJL	0.0329	1, 428	0.8562
2009	Exports at CVP	0.0223	1, 428	0.8813

[a] Significant at 5% level

Table 7-4
Results of Multivariate Analyses of Route Entrainment at the Head of Old River in 2010

Model Type	Covariate[a]	Estimate	S.E.	t-Test		
				t	df	P
Flow	Intercept	-0.5463	0.1473	-3.710	426	0.0002
	Q_A	0.3302	0.1054	3.134	426	0.0018
	Q_B	-0.2623	0.1022	-2.568	426	0.0106
	Barrier	0.7947	0.2022	3.930	426	< 0.0001
Goodness-of-fit: χ^2=17.3751, df=18, P=0.4975; AIC = 566.94						
Flow Proportion	Intercept	-0.5432	0.1471	-3.693	427	0.0003
	pQ_A	0.3944	0.1089	3.623	427	0.0003
	Barrier	0.7828	0.2018	3.880	427	0.0001
Goodness-of-fit: χ^2=13.9929, df=18, P=0.7296; AIC = 567.00						
Velocity	Intercept	-0.5470	0.1472	-3.718	426	0.0002
	V_A	0.3606	0.1099	3.282	426	0.0011
	V_B	-0.3044	0.1066	-2.856	426	0.0045
	Barrier	0.7966	0.2023	3.938	426	< 0.0001
Goodness-of-fit: χ^2=12.6394, df=18, P=0.8125; AIC = 567.80						

[a] continuous covariates (Q_A, Q_B, V_A, V_B, pQ_A) are standardized

velocity (r=0.28) at SJL and flow at OH1 during times of fish passage in 2010, although there was moderate correlation between changes in flow at SJL and observed velocity at OH1 (r=-0.48), and between changes in flow at OH1 and observed velocity at SJL (r=0.53). Observed flow proportion into the San Joaquin River at times of fish passage ranged in value from 25% to 62% (average = 48%), and was highly correlated with flow measured at SJL (r=0.91). Because flow was never reversed in the San Joaquin River during the time of fish passage in 2010, the reverse flow covariate (uQ_{iA}) was always equal to 1, and so was omitted from the analyses. There was little variation in CVP exports during fish passage through the head of Old River in 2010 (830 – 1,506 cfs, average = 928 cfs), with only slightly more variation in SWP exports (0 – 709 cfs, average = 574 cfs). Combined exports throughout the Delta ranged from 1,541 to 1,760 cfs (average = 1,663 cfs). There was little or no observed correlation between flow and velocity measures and measures of exports at either CVP, SWP, or combined (|r|<0.3).

Results of the single-variate analyses relating route entrainment at the head of Old River to river conditions found significant effects of changes in barrier status (on *vs.* off; P=0.0002), flow proportion into Old River (P=0.0003), flow (P=0.0027) and velocity (P=0.0077) measured at SJL at time of fish passage, and flow at OH1 at time of fish passage (P=0.0286) (Table 7-3). No other covariates were significant at the 5% level.

Multivariate analyses also found significant effects of flow and velocity at both the SJL and OH1 gaging stations, as well as flow proportion into the San Joaquin River and barrier status (Table 7-4). All three models (flow, velocity, and flow proportion) adequately fit the data (P>0.4). AIC detected little difference among the three models (ΔAIC ≤ 0.86), and estimated regression coefficients were similar among the three models (Table 7-4). The flow model had the lowest AIC, and predicted the route entrainment probability according to:

$$\widehat{\psi}_A = \frac{exp(0.35 + 0.0005Q_A - 0.0008Q_B)}{1 + exp(0.35 + 0.0005Q_A - 0.0008Q_B)}$$

when the barrier was off, and

$$\widehat{\psi}_A = \frac{exp(1.15 + 0.0005Q_A - 0.0008Q_B)}{1 + exp(1.15 + 0.0005Q_A - 0.0008Q_B)}$$

when the barrier was on.

When flow at OH1 was fixed at its mean observed value when tagged fish were passing (2,777 cfs), increases in flow at SJL were predicted to increase the probability of a tagged fish remaining in the San Joaquin River (Figure 7-3). For flow at SJL fixed at its mean observed value (2,595 cfs), increases in flow at OH1 were predicted to decrease the probability of a tagged fish remaining in the San Joaquin River (Figure 7-4). Regardless of the flow level at either

Figure 7-3
Fitted Probability of Remaining in the San Joaquin River at the Head of Old River versus River Discharge Measured at the SJL Gaging Station near Lathrop, CA, for River Discharge at OH1 Gaging Station in Old River Fixed at its Average (2,777 cfs), with 95% Confidence Bands, in 2010. Barrier is Non-Physical Barrier at Head of Old River

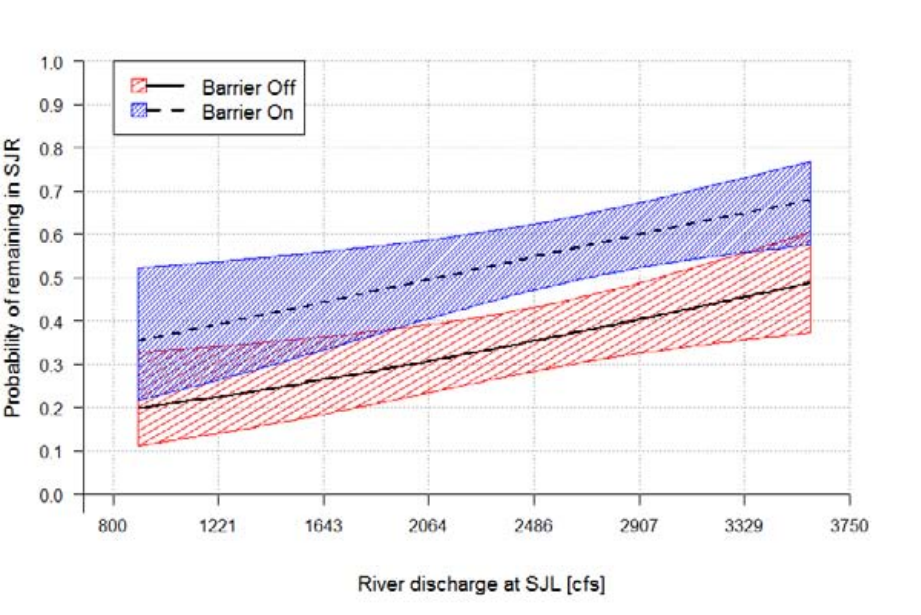
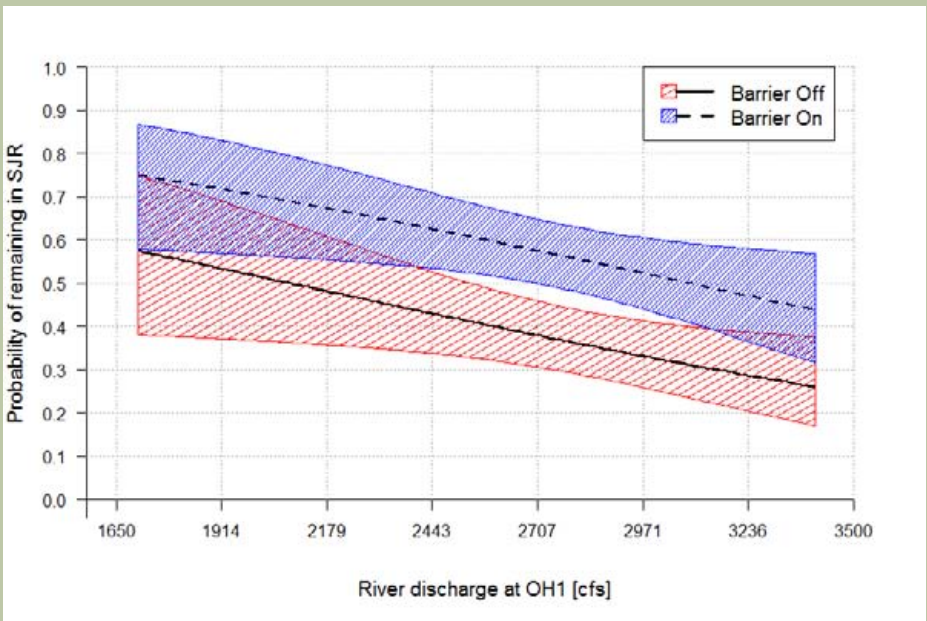


Figure 7-4
Fitted Probability of Remaining in the San Joaquin River at the Head of Old River versus River Discharge Measured at the OH1 Gaging Station in Old River, for River Discharge at SJL Gaging Station near Lathrop, CA, Fixed at its Average (2,595 cfs), with 95% Confidence Bands, in 2010. Barrier is Non-Physical Barrier at Head of Old River



OH1 or SJL, the probability of remaining in the San Joaquin River at the head of Old River was predicted to be higher when the non-physical barrier was turned on than when it was turned off (Figures 7-3 and 7-4; Table 7-4).

Summary

Both the 2009 and 2010 analyses found that increases in flow measured in the San Joaquin River near Lathrop (SJL) were associated with increased probability of remaining in the San Joaquin at the head of Old River. However, the 2009 analysis found an interaction effect between barrier status and flow measured in Old River near its head (OH1), with increases in Old River flow associated with increased probability of entering Old River when the barrier was off, but not when the barrier was on. In 2010, increases in Old River flow were associated with increased probability of entering Old River regardless of barrier status. More fish stayed in the San Joaquin River under all flow conditions in 2010 when the barrier was on than when it was off.



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APPENDIX J

Recommended Aspects of a Pilot Predatory Fish Relocation Study

The only available published Sacramento–San Joaquin Delta (Delta) study of predator control efforts (Cavallo et al. 2013) serves as a potential template for the type of study that might be considered as a pilot predator relocation effort at the Head of Old River (HOR) study area. Such a new study would have direct relevance to inform the proposed Bay Delta Conservation Plan (see Section K.2, "Predation Reduction," in Appendix K, "Relevant Aspects of the Proposed Bay Delta Conservation Plan"). The results of the present study (see Chapter 6, "Results," and Chapter 7, "Discussion") could guide any future pilot predator relocation efforts. The recommended features of any pilot predator relocation study should include the following:

- Before/after control impact (BACI) study design:
  - Predator relocation should occur from an impact area (e.g., the HOR study area), with one or more control areas (e.g., reference sites 1, 2, and 4 from the present study).
  - Depending on the resources available, it may be advantageous to vary the control sites and impact sites to provide tests of predator relocation feasibility under varying circumstances (e.g., abiotic and biotic habitat parameters, season). This may be especially relevant if predation at the control sites is similar or greater in magnitude than at the HOR study area.
- Survival of managed species through the HOR study area should be the main response variable of interest:
  - For the HOR study area, this would be primarily acoustically tagged juvenile Chinook salmon.
  - Other species of interest would include juvenile steelhead, notwithstanding the issues in determining survival of this species from acoustic tagging (see subsection "Chinook Salmon Compared to Steelhead" in Section 7.1.4, "Juvenile Salmonid Routing Including Barrier Effects" of Section 7, "Discussion").
  - Sufficient numbers of individuals and releases would be needed to establish survival estimates robust enough to discriminate changes of management significance (and management should provide guidance on establishing criteria to determine what such a level of change would be).
- Changes in predator abundance should be a secondary response variable of interest:
  - The catch per unit effort and cumulative catch during the relocation/removal phase of the study would provide a measure of the effectiveness of the capture methods implemented, as undertaken by Cavallo et al. (2013). Predator capture efforts should cover a wide range of age, sexual maturity, and sex of all potential predatory fish species.
  - In addition to changes in abundance generated during predator capture/relocation, other supplementary methods could be used (e.g., hydroacoustics, as in the present study; see, for example, Section 6.3, "Behavior and Density Changes in Predatory Fishes" in Section 6, "Results").
- Results from the present study should be used to identify areas, timing, and/or habitat conditions to target for fish removal and methodological considerations:
  - The scour hole and adjacent areas in the San Joaquin River below the Old River divergence clearly deserve emphasis on predatory fish capture efforts, but some coverage throughout the area may be

desirable because of the large fish that were shown to exist throughout the area in the side-looking mobile hydroacoustic surveys (see subsection on "Areas Occupied and Diel Changes in Depth" in Section 6.3.2, "Hydroacoustic data", of Section 6, "Results").

  - To reduce capture bias, differing sampling methods should be investigated and incorporated (e.g., electrofishing may be appropriate for nearshore areas, whereas active capture may be required in offshore areas, and other means may be required at the scour hole).

  - Depending on the resources available, it may be advantageous to acoustically tag predators proposed for relocation to identify and account for resident and homing behaviors.

- Variable intensity of effort:

  - Differing levels of capture/relocation effort should be compared to determine what level is necessary to achieve an effect (e.g., whether daily removal gives the same effect as removal every other day).

- Holding of captured predatory fish in net pens:

  - As with Cavallo et al. (2013), predatory fish could be captured and held in net pens until the study was completed, avoiding the need to sacrifice the predatory fishes.

  - Ancillary studies could be undertaken on these fish (e.g., examination of stomach contents by gastric lavage immediately after capture, documentation of growth rate based on a known ration; this could be useful for bioenergetics modeling).

- Consideration of bycatch, particularly listed species:

  - Different methods would need to be evaluated for the relative risk to listed species, both during study planning and by documentation of catch during the study.

  - Permit terms for any predator relocation pilot study would be likely to limit the potential capture gear (or its intensity of use), in any case.

- Inclusion of important covariates in assessed changes in survival:

  - As demonstrated by Cavallo et al. (2013), factors such as changes in discharge also may be important and should be studied and included in integrated analyses, if appropriate.

  - The present study found that visibility (light level and turbidity) were associated with different survival rates in the HOR study area, and this should be considered further.

- Careful documentation of personnel, equipment, time requirements, and resulting costs:

  - Such documentation would inform the cost estimates associated with Conservation Measure 15 (Localized Reduction of Predatory Fishes) in the public draft Bay Delta Conservation Plan (DWR 2013).

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APPENDIX K

Relevant Aspects of the Proposed Bay Delta Conservation Plan

The public draft Bay Delta Conservation Plan's (BDCP's) conservation strategy proposes two conservation measures that are directly relevant to management activities at the Head of Old River (HOR) study area (DWR 2013): Conservation Measure 1 (Water Facilities and Operation) includes an operable HOR gate, and Conservation Measure 15 (Localized Reduction of Predatory Fishes) includes actions to reduce predation at known hotspots within the BDCP plan area, including the HOR study area. More details about each of these measures are provided herein in Sections K.1, "Operable HOR Gate," and K.2, "Predation Reduction." The public draft BDCP also proposes Conservation Measure 16 (Nonphysical Fish Barriers), which includes the use of non-physical barriers similar to those tested at the HOR study area (Bowen et al. 2012; Bowen and Bark 2012; the present study) and Georgiana Slough (DWR 2012; Perry et al. 2012) to route covered fish species along migration pathways that have better survival prospects. This is not discussed further because of the BDCP's proposal for an operable HOR gate. In addition, the revised administrative draft BDCP also proposes various conservation measures for habitat restoration near the HOR study area, which are outlined in Section K.3, "South Delta Habitat Restoration."

K.1 OPERABLE HOR GATE

The public draft BDCP's Conservation Measure 1 (Water Facilities and Operation) includes an operable HOR gate, described as follows (DWR 2013: 3.4–13):

> A new permanent, operable gate at the Head of Old River (at the divergence from the San Joaquin River) would be constructed and operated to protect outmigrating San Joaquin River salmonids in the spring and to provide water quality improvements in the San Joaquin River in the fall. Operation of the gate can vary from completely open (laying flat on the channel bed) to completely closed (erect in the channel, prohibiting all flow from the San Joaquin River to Old River), with the potential for operations in between that would allow partial flow. The actual operation of the gate would be determined by real-time operations based on actual flows and/or fish presence.

The draft environmental impact report/statement for the BDCP describes the gate as approximately 64.0 meters long by 9.1 meters wide, with a top elevation of 4.6 meters (North American Vertical Datum of 1988); seven bottom-hinged gates would be in place, approximately 38.1 meters long (DWR et al. 2013: 3C–44). A vertical slot, self-regulating fishway with four sets of baffles would be provided for passage of adult salmonids and sturgeon. The approximately 12.2-meter-long by 3.0-meter-wide fishway would be constructed of reinforced concrete and would be designed according to National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service guidelines for Chinook salmon, steelhead, and green sturgeon. Stoplogs would be used to close the fishway when not in use. The final main component of the operable HOR gate would be a boat lock, 6.1 meters wide by 21.3 meters long (DWR et al. 2013: 3C–44). The boat lock would be constructed of sheet piles and would include two 6.1-meter-wide by 3.0-meter-high bottom-hinged gates on each end.

The public draft BDCP describes the real-time operations of the operable HOR gate as follows (DWR et al. 2013: 3.4–27):

> The gate will be managed under RTOs [real time operations] from January 1 through June 15, and October 1 through November 30, based on real-time monitoring for the presence/absence of covered fishes, hydrologic conditions, and species risk. In determining the opening and closure of the Head of Old

River gate, the fish and wildlife agencies' goal is to have the gate closed as much as possible in February through June 15; however, the gate may be open subject to RTO for purposes of water quality, stage, and flood control considerations. The final BDCP document will provide operational guidance for use by project operators in implementing these provisions.

Final designs and operation of the gate in an implemented BDCP may differ from the prior description.

K.2 NONNATIVE PREDATORY FISHES REDUCTION

The public draft BDCP's Conservation Measure 15 (Localized Reduction of Predatory Fishes) proposes to "reduce populations of nonnative predatory fishes at specific locations and eliminate or modify holding habitat for nonnative predators (predators) at selected locations of high predation risk (i.e., predation 'hotspots')" (DWR 2013: 3.4-294). The intent of the conservation measure is to relieve predation pressure at locations of concern, rather than to "entirely remove predators at any location or substantially alter the abundance of predators at the scale of the Delta system." (DWR 2013: 3.4-294). A number of predation hotspots are identified in the conservation measure, including the HOR. Conservation Measure 15 is proposed to include the following elements (DWR 2013: 3.4-300):

- Hotspot pilot program. Implement experimental treatment at priority hotspots, monitor effectiveness, assess outcomes, and revise operations with guidance from the Adaptive Management Team.

- Research actions. Via the adaptive management program, support focused studies to resolve key uncertainties.

If demonstrably effective, the hotspot pilot program will be developed in three successive stages. During the first stage, a few treatment sites will be experimentally evaluated to test the general viability of various predator reduction methods. Secondary reduction actions, such as removal of abandoned vessels, may be implemented to determine if they will be effective on a large scale. After the initial scoping stage is complete, and if shown to be effective, the second stage will consist of implementation of a pilot program with a larger range of treatment sites and refined techniques, incorporating what is learned from the first stage. The main focus at this stage is to study the efficacy of predator reduction on a larger scale to determine whether it is making a demonstrable difference and/or has any unintended ecological consequences (i.e., unexpected changes to foodweb dynamics that may have negative effects on covered fish species). The pilot program may include such activities as direct predator reduction at hotspots (e.g., Clifton Court Forebay, head of Old River scour hole, the Georgiana Slough sites, and SWP/CVP salvage release sites) and removal of old human-made structures (e.g., pier pilings, abandoned boats).

To minimize uncertainty about the appropriate management regime necessary to maintain and enhance survival of covered fishes, effectiveness monitoring will be implemented with the pilot program. The pilot program would begin with a preliminary assessment phase to compare two approaches for reducing local predator abundances: removal of predator hotspot structures (e.g., abandoned boats, derelict pier pilings) and general predator reduction in reaches with known high predation loss.

The pilot program will be carefully monitored and refined to determine whether either of these practices is effective. If the pilot program shows that the main issues are resolvable, the third stage would consist of

a defined predator reduction program (i.e., defined in terms of predator reduction techniques and the sites and/or areas of the Plan Area where techniques will be employed). Research and monitoring would continue throughout the duration of the program to address remaining uncertainties and ensure the measures are effective (i.e., that they reduce numbers and densities of predators and increase survival of covered salmonids).

The conservation measure description outlines guidelines and techniques for pilot projects under the hotspot pilot program, with the experimental portions emphasizing some of the main principles used by Cavallo et al. (2013) and described in Appendix J, "Recommended Aspects of a Pilot Predatory Fish Relocation Study" (e.g., before and after studies; DWR 2013: 3.4-303). Potential methods of localized predatory fish reduction are discussed in relation to advantages and limitations, with a number of methods deemed feasible (e.g., electrofishing, hook and line, passive trapping, gill netting, active capture—trawling/beach seining and lottery fishing with volunteer anglers), and several described as unsuitable or infeasible (e.g., dewatering/water level fluctuation, chemical treatment—rotenone, pulsed pressure waves, and release of hatchery-reared prey fish containing oral piscicide). The types of habitat favorable to nonnative predatory fish that may be modified or eliminated include features such as submerged human-made structures (e.g., abandoned boats, derelict structures, bridge piers), water diversion facilities (e.g., intakes, forebays), channel features (e.g., the scour hole at the HOR study area), and salvage release sites (DWR 2013: 3.4–308).

The BDCP's Conservation Measure 15 would benefit from knowledge gained as a result of any scour hole alteration or predator relocation research efforts undertaken at the HOR (see Section "Study Feasibility of Physical Habitat Reconfiguration," and Section "Conduct a Pilot Predatory Fish Relocation Study"). Communication and coordination of efforts before BDCP implementation would allow refinement of the conservation measure, particularly with respect to feasibility and cost. Cost assumptions are presented in the public draft BDCP (DWR 2013: 8-40).

The results of the present study and other existing studies already have the power to inform uncertainties regarding the proposed Conservation Measure 15. For example, daily predator reduction/relocation appears warranted, based on the often-short residence time and appreciable turnover of predatory fish at the HOR study area (see Section 7.3.1, "Residence Time of Predatory Fishes" in Section 7, "Discussion") and elsewhere (e.g., Cavallo et al. 2013a). However, as noted in Appendix J, "Recommended Aspects of a Pilot Predatory Fish Relocation Study," experimentation with differing levels of predator relocation intensity would be informative to guide optimization of effort. The broad seasonal window for predator reduction/relocation may be narrowed based on seasonality of the fish species, size, and sexual maturity at the HOR study area (see Section 7.3.3, "Changes in Density of Predatory Fishes"). Covered fish seasonality (e.g., outmigration timing of juvenile Chinook salmon from the San Joaquin basin) also clearly is a relevant factor, as is the potential for recovery of spring-run Chinook salmon under the San Joaquin River Restoration Program that may give broader outmigration (and emigration) timing. Changes to the level of effort applied to predator reduction/relocation efforts may be warranted based on hydrologic and other conditions on an annual basis or within specific years. In the present study, large-fish density was associated negatively with discharge (see Section 7.3.3, "Changes in Density of Predatory Fishes"), and juvenile Chinook salmon survival was associated positively with turbidity (see Section 7.2, "Predation on Juvenile Salmonids, Including Barrier Effects"). Perhaps more predator reduction/relocation effort would have been justified in 2012 than 2011, for example.

K.3 SOUTH DELTA HABITAT RESTORATION

The proposed BDCP includes several conservation measures intended to improve Delta habitat for covered species, including fish, of which some would be in the south Delta subregion close to the HOR study area (DWR 2013). Conservation Measure 4 (Tidal Natural Communities Restoration) proposes restoration of a minimum of 5,000 acres of tidal freshwater emergent wetland, tidal perennial aquatic, and tidal mudflat habitat in the south Delta Restoration Opportunity Area (ROA); the southeastern edge of this ROA is immediately adjacent to the HOR study area (see Figure 5E.4-1 in DWR 2013). Conservation Measure 5 (Seasonally Inundated Floodplain Restoration) proposes restoration of up to 10,000 acres of seasonally inundated floodplain in the south Delta area. Conservation Measure 6 (Channel Margin Enhancement) proposes enhancement of 20 miles of channel margin, primarily in the north Delta (e.g., mainstem Sacramento River, Sutter/Steamboat Sloughs), but with some smaller extent (e.g., 5 miles) possible in other areas such as the San Joaquin River near the HOR study area. Conservation Measure 7 (Riparian Natural Community Restoration) proposes to restore native riparian forest and scrub in association with Conservation Measures 4 through 7: 2,300 acres by year 15 of the BDCP, and 5,000 acres by year 40 of the BDCP. At least 3,000 acres of the restoration is proposed to take place in restored floodplains associated with Conservation Measure 6, and, therefore, would occur in the south Delta subregion.

The South Delta Habitat Working Group (SDHWG) was convened by the California Department of Water Resources in summer 2011 to identify opportunities for improving habitat in the southern part of the Delta for integration into the BDCP (ESA PWA 2013). Although flood management is not an objective of the BDCP process, the habitat improvements identified by the SDHWG were developed in a way that integrates flood management considerations and other economic benefits. As part of the SDHWG's efforts, several conceptual restoration corridors have been analyzed for their potential to provide a combination of ecological benefits to covered species (e.g., fall-run Chinook salmon from the San Joaquin River region) and flood control (see Figure EA.1.1-1 in ESA PWA 2013):

- Corridor 1A: Levee setbacks on both banks of the San Joaquin River from Vernalis to Interstate 5.
- Corridor 1B: An alternative version of Corridor 1A along the San Joaquin that includes only a right-bank levee setback and connection of Walthall Slough with the San Joaquin River via a weir.
- Corridor 2A: Expansion of the Paradise Cut flood bypass and modifications to Paradise Cut weir.
- Corridor 2B: An expanded version of Corridor 2A that also includes levee removal around Fabian Tract. Corridor 2B is essentially Corridor 2A plus Fabian Tract.
- Corridor 3: Selected levee setbacks along Middle River on Union Island.
- Corridor 4: Levee setbacks on Roberts Tract along the left bank side of the San Joaquin River and on a short reach of the right bank of Old River.

As noted by ESA PWA (2013:EA.1-2), while developed at an early, conceptual level of detail, work to-date suggests that these corridors would support achievement of the BDCP Conservation Measures 4 through 7, and simultaneously achieve ancillary benefits in flood risk reduction.

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