Final

2012 Georgiana Slough Non-Physical Barrier Performance Evaluation Project Report

California Department of Water Resources

December 2015

Final

2012 Georgiana Slough Non-Physical Barrier Performance Evaluation Project Report

Prepared by:

California Department of Water Resources
1416 9th Street
Sacramento, CA 94236-001
Contact: Ryan Reeves
916.653.6868

December 2015

This report was prepared under the supervision of

Jacob McQuirk .... Chief, Temporary Barriers and Lower San Joaquin

Ryan Reeves .... Senior Water Resources Engineer

This page intentionally left blank.

ACKNOWLEDGMENTS

The following individuals, agencies, and organizations contributed to the 2012 Georgiana Slough Non-Physical Barrier Performance Evaluation Project.[1]

Key Report Contributors	
Ryan Reeves, P.E.	California Department of Water Resources
Jacob McQuirk, P.E.	California Department of Water Resources
Mike Cane	California Department of Water Resources
Noah Adams	U.S. Geological Survey
Russell Perry, Ph.D.	U.S. Geological Survey
Jason Romine, Ph.D.	U.S. Geological Survey
Theresa Liedtke	U.S. Geological Survey
Jon Burau	U.S. Geological Survey
Aaron Blake	U.S. Geological Survey
Mike Horn, Ph.D.	U.S. Bureau of Reclamation
Chris Fitzer	Environmental Science Associates
Steve Pagliughi	AECOM Technical Services, Inc.
Roy Leidy	AECOM Technical Services, Inc.
Chuck Hanson, Ph.D.	Hanson Environmental, Inc.
Sam Johnston	Hydroacoustic Technologies, Inc.
Kevin Kumagai	Hydroacoustic Technologies, Inc.
Kenneth Cash	Normandeau Associates, Inc.

Project Collaborators	
California Department of Water Resources	Project Sponsor, Lead Project Manager/Implementing Agency, Data Analysis, and Report Contribution and Review
U.S. Bureau of Reclamation	Field Implementation, Data Analysis, and Report Contribution
U.S. Geological Survey	Field Implementation, Data Analysis, and Report Contribution
California Department of Fish and Wildlife	Field Implementation
AECOM Technical Services, Inc.	Consultant Team Project Manager, Field Implementation, Data Analysis, and Report Contribution
Environmental Science Associates	Data Analysis, Report Contribution and Coordination
Hydroacoustic Technologies, Inc.	Field Implementation, Data Analysis, and Report Contribution
Hanson Environmental, Inc.	Co-Principal Investigator, Field Implementation, Data Analysis, and Report Contribution
Normandeau Associates, Inc.	Field Implementation, Data Analysis, and Report Contribution
Turnpenny Horsfield Associates, Ltd.	Co-Principal Investigator, Data Analysis, and Report Contribution
Professional Aquaculture Services	Field Implementation Support

Additional Acknowledgments

The project team would also like to acknowledge and thank the many people who provided valuable input on the project study plan, field support, data analysis, report review, and document production. These individuals and organizations include: Bill McLaughlin, Ben Geske, Genny Schrader, Khalid Ameri, John Personeni, and numerous additional staff at the California Department of Water Resources and the U.S. Geological Survey's

[1] Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government or State of California.

Columbia River Research Laboratory. The project team also thanks Cal-Neva Construction Services, CS Marine Constructors, and Big Valley Divers for providing barrier construction and maintenance support. We would also like to thank the U.S. Fish and Wildlife Service's Coleman National Fish Hatchery and California – Nevada Fish Health Center for providing the late fall–run Chinook salmon and steelhead used in the study and laboratory facilities for the tag retention and fish health evaluation.

Project Report Reviews

The 2012 Georgiana Slough Non-Physical Barrier Performance Evaluation Project Report has gone through several technical review processes. The review processes included editorial (technical editor), contributor reviews (primary report authors; see previous), management review (California Department of Water Resources, Bay-Delta Office management), external review (independent science experts), and draft final reviews by California Department of Water Resources' Bay-Delta Office Chief, South Delta Branch Chief, and Temporary Barriers and Lower San Joaquin Chief. All comments received during the review processes were addressed, resolved, and closed and a review certification by the California Department of Water Resources' Bay-Delta Office Project Manager (Ryan Reeves) and contractor Project Manager (Chris Fitzer, Environmental Science Associates) is provided herein. A summary of Project Report reviews follows:

- Project team/contributor review, including review by staff from California Department of Water Resources, U.S. Geological Survey, AECOM Technical Services, Inc., Environmental Science Associates, Hanson Environmental, Inc., Hydroacoustic Technologies, Inc., and Normandeau Associates, Inc. (July 2013);
- Draft review by California Department of Water Resources, Bay-Delta Office management (September 2013);
- External (independent) technical draft review by Dr. Marin Greenwood, Dr. Mark D. Bowen, and Dr. Cynthia LeDoux-Bloom (November 2013);
- Draft Final review by California Department of Water Resources, Bay-Delta Office management (October 2014); and
- Draft Final review by California Department of Water Resources, Bay-Delta Office management (December 2014).

Review certification:

Ryan D. Reeves 2/5/16
Ryan Reeves Date

Roy Leidy 2/5/16
Roy Leidy Date

TABLE OF CONTENTS

Appendices

Figures

Tables

ACRONYMS AND OTHER ABBREVIATIONS

^{o}C	degrees Celsius
µPa	micropascal
2D	two-dimensional
3D	three-dimensional
ADCP	acoustic Doppler current profiler
AIC	Akaike's Information Criterion
ATR	Acoustic Tag Receiver
ATS	Acoustic Tag Tracking System
AUC	area under the receiver operating curve
BAFF	Bio-Acoustic Fish Fence
BIC	Bayesian Information Criterion
BL/s	body lengths per second
BiOp	*Biological and Conference Opinion for the Long-Term Operations of the Central Valley Project and State Water Project*
CDF	cumulative distribution functions
cfs	cubic feet per second
CI	confidence interval
CO_2	carbon dioxide
CVP	Central Valley Project
dB	decibel
dBht	decibel hearing threshold
DCC	Delta Cross Channel
Delta	Sacramento–San Joaquin Delta
DFW	California Department of Fish and Wildlife
DIDSON	Dual-Frequency Identification Sonar
DPM	Delta Passage Model
DWR	California Department of Water Resources
ESA	federal Endangered Species Act
FDA	U.S. Food and Drug Administration
FL	fork length
GLM	generalized linear modeling
GPS	global positioning system
GSNPB	Georgiana Slough Non-Physical Barrier
HIML	high intensity modulated light

HOR	Head of Old River
IBM	Individual-Based Model
ID	identification
kHz	kilohertz
km	kilometer(s)
m	meter(s)
mm	millimeter(s)
m/s	meter(s) per second
m^2	meters squared
NLL	negative log-likelihood
NMFS	National Marine Fisheries Service
PDFs	probability distribution functions
PVC	polyvinyl chloride
RAT	Raw Acoustic Tag
Reclamation	U.S. Bureau of Reclamation
ROC	receiver operating curve
RPA	Reasonable and Prudent Alternative
RTK	real-time kinematic
SE	standard error
SILAS	Synchronized Intense Light and Sound
SOP	standard operating procedure
SWP	State Water Project
TAT	Tracked Acoustic Tag
TL	tail length
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

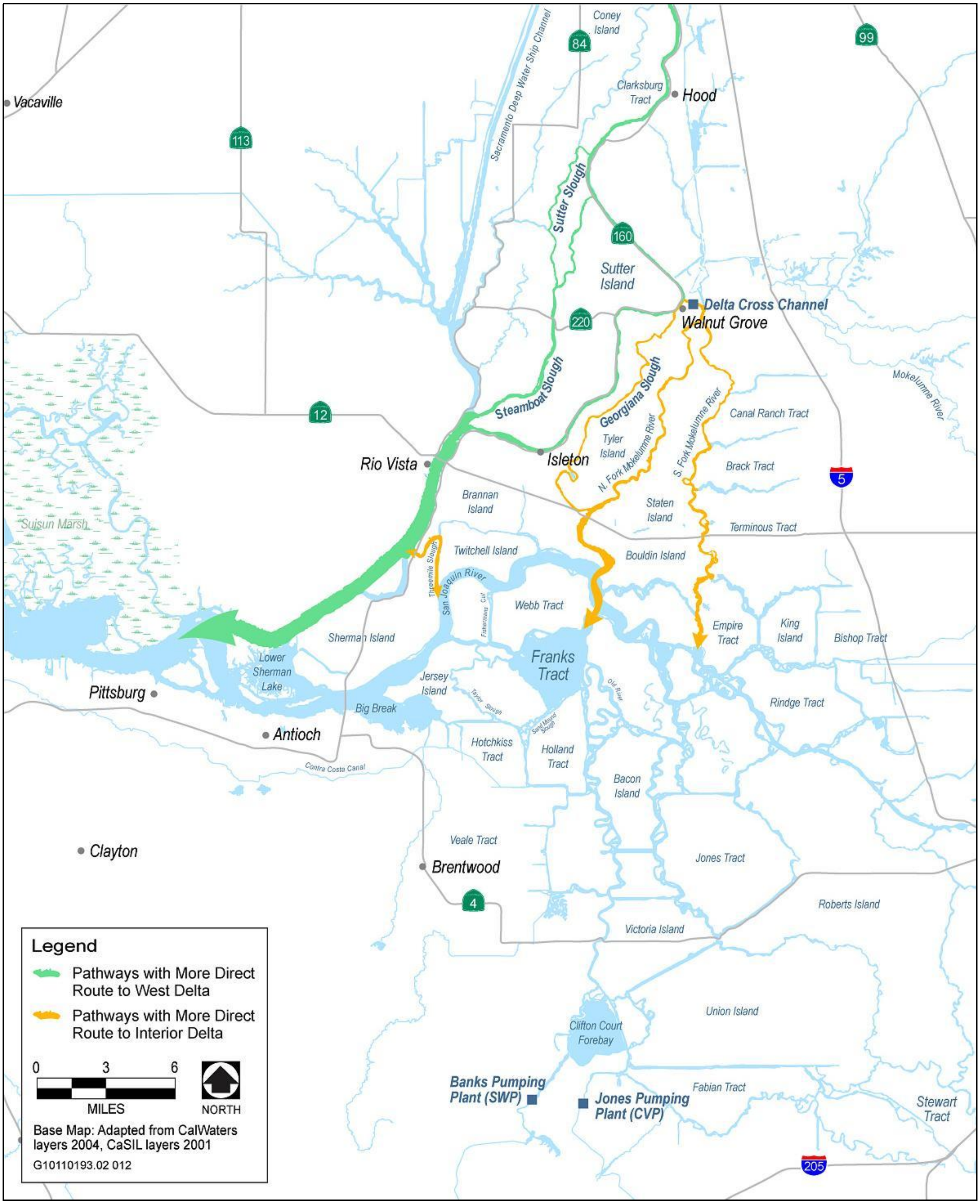
The Sacramento River and its tributaries support populations of anadromous fish species including winter-run, spring-run, fall-run, and late fall–run Chinook salmon (*Oncorhynchus tshawytscha*); and Central Valley steelhead (*O. mykiss*). Several of these species are listed as threatened or endangered under the California Endangered Species Act, federal Endangered Species Act (ESA), or both. These species spawn and rear in Sacramento River tributaries; adults use the mainstem Sacramento River for primarily upstream migration and juveniles use it for downstream migration. Juvenile Chinook salmon and steelhead migrate through the lower river during winter and spring. During their downstream migration, juvenile salmonids encounter alternative pathways, such as Sutter and Steamboat Sloughs, the Sacramento–San Joaquin Delta (Delta), Delta Cross Channel (DCC) and the North and South Forks of the Mokelumne River, Georgiana Slough, and Threemile Slough. **Figure ES-1** shows the migration pathways in the lower Sacramento River/north Delta for outmigrating anadromous salmonids, the location of the DCC, and the State Water Project (SWP) and Central Valley Project (CVP) pumping facilities in the south Delta.

Under the ESA, the National Marine Fisheries Service (NMFS) issued the 2009 *Biological and Conference Opinion for the Long-Term Operations of the Central Valley Project and State Water Project* (BiOp) for winter-run and spring-run Chinook salmon, Central Valley steelhead, and green sturgeon (NMFS 2009). Reasonable and Prudent Alternative (RPA) Action IV.1.3 of the BiOp requires the California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation) to consider engineering solutions to reduce the diversion of juvenile salmonids from the Sacramento River into the interior and south Delta.

The migration of juvenile salmonids into the interior Delta through pathways such as Georgiana Slough has been shown in previous studies (Brandes and McLain 2001; Perry 2010) to contribute to greater mortality. In an effort to identify potential engineering approaches to reduce the percentage of the juvenile salmonids that migrate from the Sacramento River into Georgiana Slough, DWR implemented a large-scale experimental testing program in 2011 and 2012 to assess the effectiveness of a non-physical barrier as a method for guiding downstream migrating juvenile salmonids. The experimental design of the 2011 and 2012 tests included the use of acoustically tagged juvenile late fall-run Chinook salmon (2011 and 2012) and steelhead (2012), released upstream of the non-physical barrier when the barrier was on and when it was off, to determine the effectiveness of the barrier. This report presents the results of the experimental tests conducted in 2012 with additional discussion of the results of tests conducted at Georgiana Slough in spring 2011.

ES.1.1 BACKGROUND

Georgiana Slough is a natural channel that allows water and fish to move from the Sacramento River into the interior Delta. Previous studies have demonstrated that juvenile Chinook salmon experience greater mortality when migrating into Georgiana Slough than those juveniles that continue to migrate downstream in the Sacramento River (Brandes and McLain 2001; Perry 2010). Movement and/or diversion of these fish into the interior and south Delta increases the likelihood of losses through predation, entrainment into non-project Delta diversions, and mortality associated with the SWP and CVP pumping facilities in the south Delta (Perry 2010; NMFS 2009). Passage of juvenile salmonids from the Sacramento River into the interior Delta through the DCC can be reduced through seasonal closure of the radial gates in late winter and spring; however, no similar



Source: AECOM 2013

Figure ES-1 **Lower Sacramento River/North Delta Migration Pathways**

protection is available to reduce the movement of juvenile salmonids from the Sacramento River into the interior Delta through Georgiana Slough. Flows into Georgiana Slough improve water quality by reducing salinity in the interior Delta and provides free access to the interior Delta, which encourages use by recreational boaters. Because of these benefits, alternatives to the installation of a physical barrier (i.e. radial gates), are being investigated.

After evaluating results of experimental tests using various alternative non-physical barrier technologies, DWR designed and implemented a study to evaluate the performance of the Georgiana Slough Non-Physical Barrier (referred to as the GSNPB Study) in 2011 and 2012 to test the effectiveness of using a non-physical barrier, referred to as a behavioral Bio-Acoustic Fish Fence (BAFF). The BAFF combines three stimuli expected to deter juvenile Chinook salmon and steelhead from entering Georgiana Slough: sound, high-intensity modulated light (previously known as stroboscopic light), and a bubble curtain.

ES.2 STUDY PURPOSE, OBJECTIVES, AND OVERVIEW

The primary purpose of the 2012 GSNPB Study was to further test the effectiveness of a BAFF in preventing outmigrating juvenile Chinook salmon and steelhead from entering Georgiana Slough.

The objectives of the 2012 GSNPB Study were to:

- estimate the effectiveness of the BAFF in successfully deterring juvenile Chinook salmon and steelhead from entering Georgiana Slough and encouraging them to continue their migration downstream in the Sacramento River;
- determine the relative contribution of various factors, such as the status of the BAFF (on / off), water velocity, ambient light, and location of fish (2D & 3D) in the channel cross section in the Sacramento River; and
- examine the behavior, movement, and response of predatory fish, such as striped bass, near the BAFF, and develop estimates of predation on juvenile salmon and the survival of salmon passing through the study area.

The experimental tests conducted as part of the 2012 GSNPB Study provide additional data to support the feasibility study required under RPA Action IV.1.3 of the NMFS BiOp. Both the 2012 and the 2011 GSNPB studies were designed to assist DWR and Reclamation in meeting required actions for SWP and CVP compliance with the ESA and the NMFS BiOp. They also were designed to assist with informing decision making and adaptive management of the NMFS BiOp RPA actions, which could contribute to reducing adverse impacts on ESA-listed anadromous salmonids associated with long-term SWP and CVP operations.

The basic concept of the 2012 GSNPB Study was similar to that of the 2011 study: to release hatchery-raised juvenile late fall–run Chinook salmon (as well as steelhead in 2012) that have surgically implanted acoustic tags with unique codes into the Sacramento River immediately downstream from Steamboat Slough, approximately 8.9 kilometers (km) upstream from Georgiana Slough, and then to compare the proportion of tagged salmon (and steelhead) entering the study area that successfully migrated downstream in the Sacramento River when a non-physical barrier was on compared to when the barrier was off.

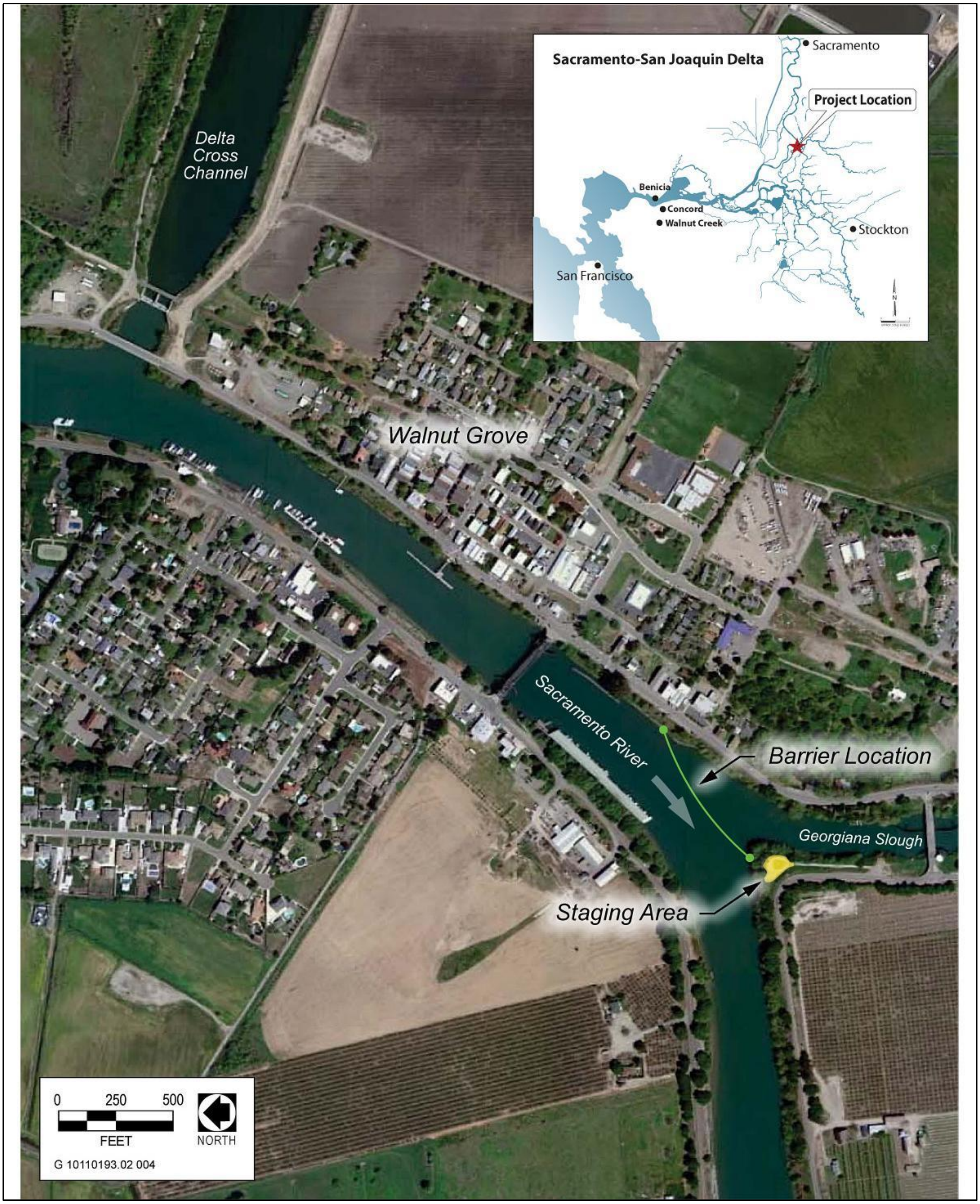
The experimental design of the study enabled testing of the response of fish encountering the Sacramento River and Georgiana Slough junction both when the barrier was on and when it was off under a range of environmental conditions (e.g., tidal conditions, day and night, Sacramento River flows, rate of flow entering Georgiana Slough). The overall goal of implementing a barrier at this location is to reduce the migration of juvenile anadromous salmonids into the interior Delta through Georgiana Slough, where they are less likely to survive and their vulnerability to entrainment into the SWP and CVP south Delta export facilities is greater (Perry 2010).

Figure ES-2 shows the study location, and **Figure ES-3** shows the conceptual design of the BAFF used at Georgiana Slough. **Figure ES-4** provides an overview of the study area, including the release location for tagged late fall–run Chinook salmon and steelhead; the location of the barrier: and the locations of the acoustic tag detection and monitoring systems, referred to as the peripheral hydrophones and study array.

ES.2.1 Key Components of 2012 Experimental Tests

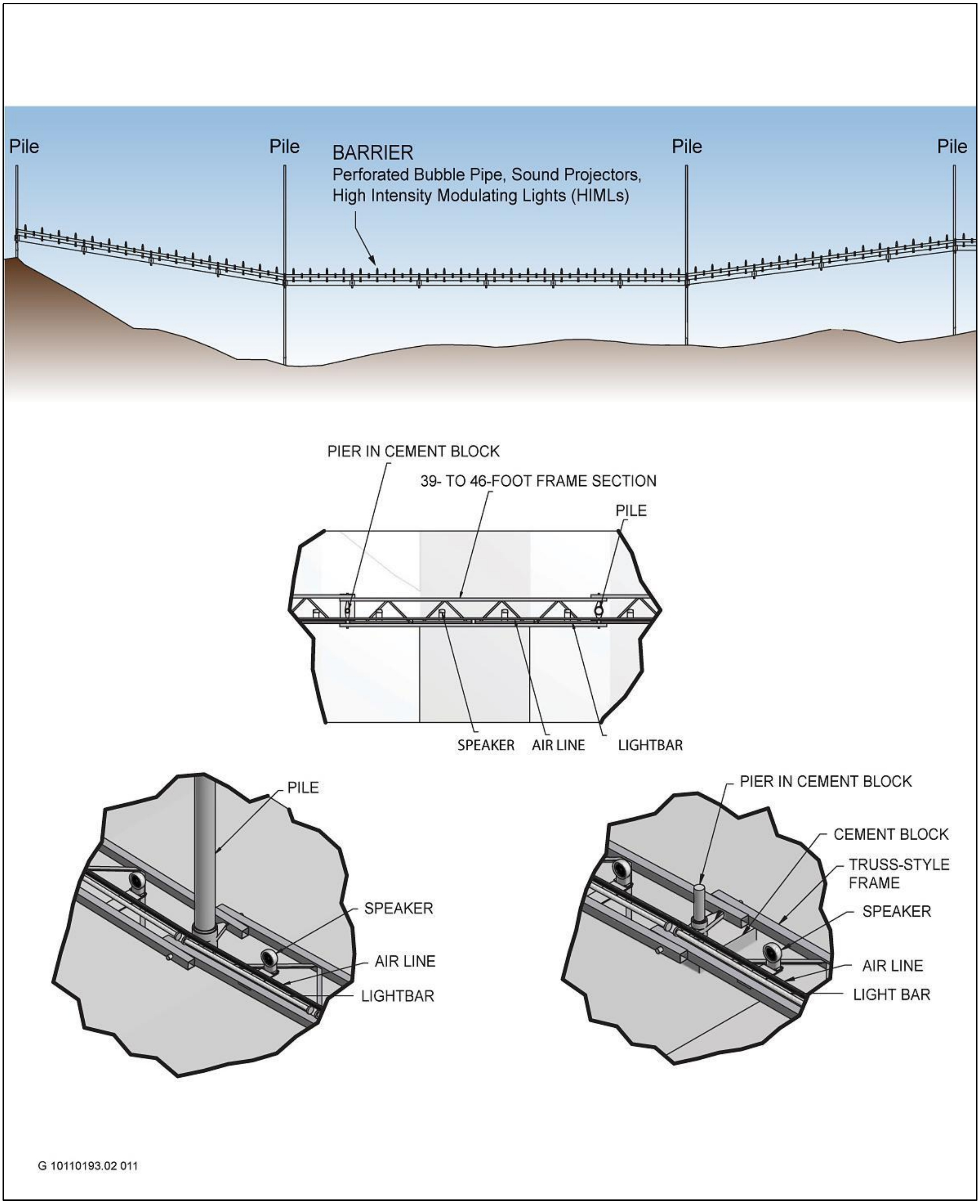
The 2012 experimental tests included the following key components:

- A total of 1,501 late fall–run Chinook salmon and 299 steelhead produced at the Coleman National Fish Hatchery were acoustically tagged and released into the Sacramento River, and their downstream migration past the non-physical barrier was monitored.
  - Fish were released every 3 hours, 24 hours a day from March 6, 2012, through April 23, 2012, during an important migration period for salmonids.
  - Releases into the Sacramento River were made approximately 8.9 km upstream from the non-physical barrier to maximize the number of fish that encounter the barrier while also allowing the fish time to adjust to the river conditions and disperse into the channel before encountering Georgiana Slough.
  - Passage of acoustically-tagged salmon and steelhead was monitored upstream from, in the immediate area of, and downstream from the barrier in the Sacramento River and Georgiana Slough both when the barrier was on and when it was off.
  - Several species of predatory fish were captured, acoustically tagged, released, and monitored to evaluate behavior, movement patterns, and potential predation of tagged juvenile Chinook salmon and steelhead in association with the presence and operations of the non-physical barrier.
  - Multiple hydrophones were installed in the Sacramento River immediately upstream from, downstream from and adjacent to the barrier to monitor movements of tagged fish as they encountered and responded to the barrier. These hydrophones are referred to as the array at the barrier or study array. The study array allowed for three-dimensional positioning of acoustic transmitters (tags). The pathway of a tag, over or under the BAFF, was determined for each tag that crossed the BAFF alignment. Additional hydrophones, referred to as the peripheral hydrophones, were installed to detect tagged fish in channels upstream and downstream from the study array (**Figure ES-4**).
- Multiple acoustic Doppler current profilers were installed in the Sacramento River in the vicinity of the barrier to monitor local currents, water velocities, and general hydrodynamics.
- Active multibeam hydroacoustic devices, including a DIDSON (Dual-Frequency Identification Sonar) camera were installed to monitor fish densities in the immediate vicinity of the barrier.



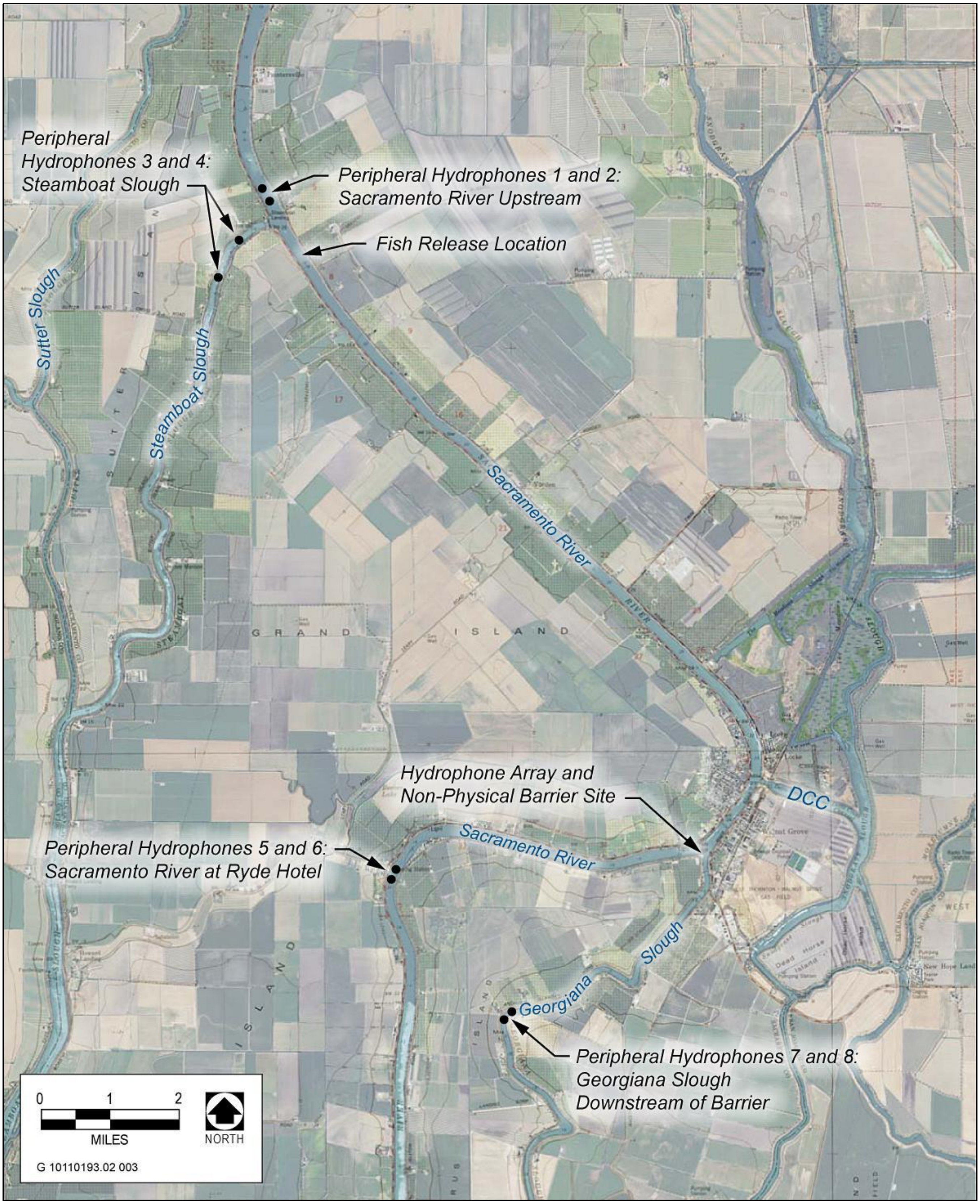
Source: Data provided by California Department of Water Resources and adapted by AECOM in 2012

Figure ES-2 **Location of 2012 Georgiana Slough Non-Physical Barrier Study**



Source: Data provided by Fish Guidance Systems and adapted by AECOM in 2012

Figure ES-3 Conceptual Design of the 2012 BAFF Used at Georgiana Slough



Source: Data provided by California Department of Water Resources and adapted by AECOM in 2012

Figure ES-4 **Overview of the 2012 Georgiana Slough Non-Physical Barrier Study Area**

ES.2.2 Barrier Performance Evaluation Metrics

The following evaluation metrics of barrier performance were compared between barrier-on and barrier-off conditions using the results of acoustic tracking in the 2012 GSNPB Study:

- *barrier efficiency*, which is evaluated in terms of:
    - *deterrence efficiency*: the proportion of tagged juvenile Chinook salmon and steelhead detected in the hydrophone array that moved away from the barrier and were deterred from entering Georgiana Slough, and instead remained in the Sacramento River;
    - *protection efficiency*: the proportion of tagged juvenile Chinook salmon and steelhead that were detected by the hydrophone array, survived to the barrier (i.e., avoided predation or other sources of mortality), moved past the barrier and reached the peripheral hydrophones downstream in the Sacramento River at Ryde Hotel, rather than reaching the peripheral hydrophones in Georgiana Slough;
    - *overall efficiency*: the proportion of tagged juvenile Chinook salmon and steelhead entering the study area (i.e., that were detected by the hydrophone array) that subsequently were detected at the peripheral hydrophones downstream in the Sacramento River at Ryde Hotel, accounting for losses of fish migrating into Georgiana Slough and predation losses in the area where the study array was located adjacent to the barrier;
- *probability of entrainment*: generalized linear modeling of tagged fish to predict fates based on several factors, including BAFF operation and environmental conditions; and
- *survival and route entrainment probabilities*: model predictions of fish survival from one location to another based on route entrainment/selection and other factors.

ES.3 STUDY RESULTS AND FINDINGS

The results and findings of the 2012 GSNPB Study are summarized below.

ES.3.1 Overall Efficiency and Entrainment Probability

- During the March 6 through April 28 period of the 2012 study, 1,501 tagged juvenile Chinook salmon were released, 269 of which were excluded from the analysis because of mortality upstream of the BAFF location. Of the 299 steelhead released, 69 were excluded from the analysis because of mortality upstream of the BAFF.
- Overall, during the 2012 tests, the BAFF reduced the percentage of Chinook salmon passing into Georgiana Slough from 24.8% when the BAFF was off to 10.3% when the BAFF was on, representing an overall reduction in entrainment into Georgiana Slough of 14.5 percentage points. The observed reduction in entrainment for juvenile Chinook salmon was highly statistically significant when the BAFF was on ($P=<0.0001$). This improvement produced an overall efficiency rate of 89.7%; that is, 89.7% of Chinook salmon that entered the area when the BAFF was on exited by continuing down the Sacramento River. The BAFF reduced the percentage of steelhead passing into Georgiana Slough from 25.6% when the BAFF was

off to 12.3% when the BAFF was on, representing an overall reduction in entrainment into Georgiana Slough of 13.3 percentage points. The improvement produced an overall efficiency rate of 87.7%; that is, 87.7% of steelhead that entered the area when the BAFF was on exited by continuing down the Sacramento River.

- Results of statistical analyses of survival and route entrainment probabilities using the 2012 data showed that for juvenile Chinook salmon the probability of entering Georgiana Slough when the BAFF was on was 11.8%, whereas the probability increased to 24.4% when the BAFF was off. For juvenile steelhead, the probability of entering Georgiana Slough was 11.6% when the BAFF was on and 26.4% when the BAFF was off. The survival of juvenile salmon from the point of release to the BAFF (78.3%) was relatively low in 2012 and considerably lower (17.4 percentage points) than survival observed during the 2011 studies (95.7%), when river flow was greater. Survival from point of release to the BAFF for steelhead was also relatively low in 2012 (66.2%). Survival rates were higher for juvenile salmonids downstream of the BAFF in the Sacramento River and lower for those fish that migrated into Georgiana Slough.

- Deterrence efficiency when the BAFF was on was greater for juvenile steelhead (69.9%) than for juvenile Chinook salmon (56.1%), suggesting that steelhead were more strongly deterred than juvenile Chinook salmon by the BAFF. No statistically significant difference was detected in either protection or overall efficiency between juvenile salmon and steelhead when the BAFF was on, suggesting that operation of the BAFF provided consistent protection and overall efficiency for both salmonid species.

- Under low light levels (<5.4 lux) when the BAFF was on, deterrence efficiency was less for juvenile Chinook salmon (49.2%) when compared to steelhead (65.7%). Protection efficiency when the BAFF was on was also less for Chinook salmon (84.2%) when compared to steelhead (100%). Overall efficiency when the BAFF was on was found to be greater for steelhead (100%) than for Chinook salmon (84.2%). The same pattern in differences was observed between steelhead and Chinook salmon under high light levels (≥5.4 lux) for deterrence and protection efficiency. In contrast, overall efficiency for steelhead (81.5%) was less than for Chinook salmon (95.0%), suggesting that steelhead may be more sensitive to the BAFF under low light conditions than under high light conditions.

- Under low approach velocity levels (<0.25 m/s) when the BAFF was on, deterrence efficiency was less for juvenile Chinook salmon (57.3%) when compared to steelhead (76.3%). Protection efficiency when the BAFF was on was slightly higher for Chinook salmon (94.5%) when compared to steelhead (92.9%). Overall efficiency when the BAFF was on was found to be greater for Chinook salmon (94.2%) than for steelhead (88.7%). Under high approach velocity levels (≥0.25 m/s) when the BAFF was on, for deterrence, protection, and overall efficiency were higher for steelhead (57.1%, 100%, and 85.7%, respectively) than for Chinook salmon (48.5%, 51.5%, and 59.1%, respectively). Yearling steelhead were larger than juvenile Chinook salmon used in these tests and likely had greater swimming performance capability, which is thought to have contributed to the greater response of steelhead to the BAFF.

- A generalized linear model (GLM) of BAFF performance was developed for juvenile Chinook salmon based on the results of the 2012 experiments. The model considered the following covariates: barrier on/off, time of day (day vs. night), Sacramento River flow[2] (cfs), cross-sectional location of each fish in the river channel,

[2] While not explicitly used as covariates, temperature and turbidity typically co-vary with flow and, therefore, flow can be considered a surrogate for these parameters.

location of the critical streakline in the channel cross section, and the location of the fish along the river axis. Model results for juvenile Chinook salmon suggested that cross-section position of the fish in the Sacramento River and BAFF operation had the largest effect on the probability of entrainment into Georgiana Slough, supporting the hypothesis that the BAFF operation affected migration route selection for juvenile Chinook salmon. The model also showed an interaction between river flow and entrainment into Georgiana Slough with greater entrainment risk as river flow increased.

- Results of a similar GLM for juvenile steelhead suggested that river flow and cross-sectional position had the largest influence on entrainment risk, with other covariates, including BAFF operation, streakline location, along-stream location, and time of day, contributing less to the risk of entrainment. Similar to results for Chinook salmon, the steelhead model showed that the risk of entrainment into Georgiana Slough increased as river flow increased. As would be expected, both Chinook salmon and steelhead that migrated along the Sacramento River channel bank that leads into Georgiana Slough had a higher probability of entrainment than those fish that migrate on the opposite bank or mid-channel. BAFF operation contributed to a reduction in risk of entrainment for both Chinook salmon and steelhead, which is consistent with results of deterrence, protection, and overall efficiency tests in showing that BAFF operation contributed to a greater probability of juvenile salmonids remaining in the Sacramento River. The results showing that the cross-sectional location of juvenile salmonids in the Sacramento River channel is a major factor in determining entrainment risk support additional consideration of management actions and approaches that would help guide the migration pathway of juvenile salmonids away from the vicinity of Georgiana Slough and closer to the middle of the channel or opposite channel bank. The 2012 results suggest that even a small lateral movement of juvenile salmonids in the Sacramento River channel can have a substantial influence on reducing the risk of entrainment into Georgiana Slough. Other studies using floating log booms and guidance fences have shown that these relatively simple structures can be effective in changing the migration path of juvenile salmonids in river environments (Scott 2012).

- Results of the 2012 studies were also used to develop a route entrainment model of the response of juvenile salmonids to BAFF operations. Model results showed that under conditions of low Sacramento River flow there is a greater risk of entrainment regardless of BAFF operations. Although the probability of entrainment increased under low river flow conditions, the BAFF On condition reduced the risk of entrainment compared to the BAFF Off conditions. These results suggest that the effectiveness of the BAFF would increase as flows in the Sacramento River increase.

- These findings show how an integrated multisensory (i.e., light, sound, air bubbles) non-physical barrier was able to reduce, but not eliminate, the probability of juvenile salmonids being entrained into Georgiana Slough.

ES.3.2 Predators and Predation

- Estimates of survival probability is one measure of the effect of predation on juvenile Chinook salmon and steelhead during their downstream migration through the study area assuming no natural mortality due to other causes such as disease. The survival probability for the Sacramento River reach between the point of fish release and the BAFF for juvenile Chinook salmon was 78%, suggesting that relatively high predation was occurring upstream of the BAFF. In contrast, the survival probability for Chinook salmon in the Sacramento River reach downstream of the BAFF was 93% when the BAFF was on and 93% when the BAFF was off, suggesting that survival, relative to predation, in this reach was independent of BAFF operation.

Survival of juvenile Chinook salmon in Georgiana Slough downstream of the BAFF was 87% when the BAFF was on and 83% when the BAFF was off. These results are consistent with earlier survival studies which also showed higher survival and lower predation losses for juvenile Chinook salmon that migrate downstream in the Sacramento River. It is important to keep in mind that these results are limited to those relatively short reaches of the river and slough where acoustic monitoring was done as part of the 2012 study.

- Survival of juvenile steelhead in 2012 showed a pattern similar to that observed for juvenile Chinook salmon. Survival in the Sacramento River between the point of release and the BAFF was 66%, suggesting high predation rates on juvenile steelhead upstream of the BAFF. Survival in the Sacramento River reach downstream of the BAFF was 88% when the BAFF was on and 94% when the BAFF was off. Survival in Georgiana Slough downstream of the BAFF was 80% when the BAFF was on and 79% when the BAFF was off. As observed with juvenile Chinook salmon, predation mortality on juvenile steelhead was greater in the reach that included Georgiana Slough in 2012 compared to survival in the Sacramento River reach downstream of the BAFF.

- Based on analysis of tagged predator data, the following conclusions were made: The small differences in occupancy rates of tagged predators in different spatial scales and among the BAFF installed condition, BAFF not installed condition, and conditions combined suggest that the BAFF's physical features had no effect on predator densities in the area immediately surrounding the BAFF. The apparent positive relationship in occupancy rate of tagged predators with increased distance from the BAFF during the BAFF On condition and the apparent negative relationship in occupancy rate with increased distance from the BAFF during the BAFF Off condition suggest predatory fish as a group showed avoidance behavior in response to the BAFF's deterrence features. Predation rate spatial patterns across all comparisons suggest the BAFF's physical and deterrence features did not contribute to increased predation in the area immediately surrounding the BAFF. It is important to note that predation rates in the study area during the study time period in the absence of a BAFF's physical and deterrence features (i.e., true baseline predation rates) are unknown; therefore, results of the study should be interpreted carefully. Predation rates in the entire study area may have been influenced by the presence and operation of the BAFF.

- Based on analysis of active hydroacoustics data, the BAFF operation appeared to have no impact on the average position of larger fish in the water column near the BAFF.

ES.3.3 Comparison of BAFF Performance between 2011 and 2012 for Juvenile Chinook Salmon

- Results of statistical analysis of the 2012 data showed that the percentage of juvenile Chinook salmon entrained into Georgiana Slough was reduced from 24.4% (BAFF Off) to 11.8% (BAFF On), a reduction of approximately one-half. During the 2011 study period, operation of the BAFF reduced the percentage of juvenile Chinook salmon passing into Georgiana Slough from 22.1% (BAFF Off) to 7.4% (BAFF On); a reduction of approximately two-thirds of the fish that would have been entrained. The magnitude of juvenile Chinook salmon migration into Georgiana Slough when the BAFF was off was similar between the two years as was the percentage reduction in the risk of entrainment into Georgiana Slough when the BAFF was on (a reduction of 12.6 percentage points in 2012 and 14.7 percentage points in 2011). In both years, operation of the BAFF contributed to a reduction in the movement of juvenile Chinook salmon from the Sacramento River into Georgiana Slough.

- Results of a comparison of the 2012 and 2011 studies using juvenile Chinook salmon found no statistically significant differences in deterrence efficiency, protection efficiency, or overall efficiency when the BAFF was on between the two years. The deterrence efficiency when the BAFF was on was 56.1% in 2012 and 50.4% in 2011. Protection efficiency when the BAFF was on was 89.0% in 2012 and 90.5% in 2011. Overall efficiency when the BAFF was on was 89.7% in 2012 and 90.8% in 2011. Similarly, no significant differences were detected in deterrence, protection, or overall efficiency when the BAFF was on under low and high light levels or during low and high water velocities between 2012 and 2011. These results suggest that despite the large differences in Sacramento River flows during the 2012 and 2011 surveys, operation of the BAFF provided consistent protection and overall efficiency in reducing the risk of juvenile Chinook salmon entrainment into Georgiana Slough.

- The estimated survival probability for juvenile Chinook salmon in the Sacramento River upstream of the BAFF (from point of release to the BAFF) in 2012 was 78.3%, which was 17.4 percentage points lower than the survival estimated in 2011 (95.7%). Flows and turbidity in the river were lower in 2012 compared to 2011, which may have contributed to greater predation mortality in the river upstream of the BAFF. It is hypothesized that high flows in the Sacramento River and corresponding increased water velocities and turbidity levels may have contributed to the relatively low level of predation on juvenile Chinook salmon estimated during the 2011 tests. Based on the similarity between estimates of protection and overall efficiency observed in both the 2012 and 2011 studies, the effects of predation on juvenile Chinook salmon in the immediate vicinity and downstream of the BAFF were low.

- Analysis using GLM for both the 2012 and 2011 study results found that river discharge, which is a function of velocity, the cross-sectional location of the fish in the Sacramento River, and BAFF operations, was an important predictor of fish behavioral response to the BAFF and entrainment into Georgiana Slough in both years of the study.

- Results of the 2012 tests, showed that at substantially lower Sacramento River flow rates, BAFF operation consistently reduced the probability that juvenile Chinook salmon would be entrained into Georgiana Slough. Simulation model results using the 2012 test data showed that under very low Sacramento River flows, tidally driven reverse flow into Georgiana Slough increases the risk of juvenile Chinook salmon entrainment, although operation of the BAFF is predicted to reduce this risk. Under relatively high river flows during the 2011 tests (approximately 43,000–45,000 cfs river flow entering the river junction at Georgiana Slough), operation of the BAFF also consistently reduced the probability that juvenile Chinook salmon would be entrained into Georgiana Slough.

- The interaction of the cross-sectional position of the fish with river flow was the predominant factor that influenced the risk of juvenile salmonids entrainment into Georgiana Slough. Under the GLM, the location of a fish in the river channel cross-section was the most important driver of an individual fish's probability of entrainment into Georgiana Slough in both 2012 and 2011. Under conditions of relatively lower river flow and velocity in 2012 (compared to 2011), juvenile salmonids may have a greater opportunity to respond to the BAFF and flows entering Georgiana Slough, although results of the 2012 study were consistent with those from 2011 in showing that the location of fish in the river channel is a strong influence on the risk of entrainment into Georgiana Slough. Under the high flow (and high-velocity) conditions in 2011, operation of the BAFF was less effective for fish located close to the east side of the river channel (downstream river left). These results suggest that fish in this area cannot behaviorally respond to the BAFF and swim away from it fast enough under high river flow conditions to avoid being swept across the barrier and into Georgiana Slough.

- Although varying light conditions did not appear to affect juvenile salmonid entrainment into Georgiana Slough or BAFF efficiency results, turbidity levels were relatively low during the 2012 study period and high during the 2011 study period. High turbidity in 2011 likely muted the BAFF's light intensity and limited the use of visual cues for juvenile salmonids to be guided by the BAFF during the daytime. This muting may have led to similar performance between daytime and nighttime tests; however, results of the 2012 study, under lower turbidity conditions showed a pattern similar to that from the 2011 study.

- Results from the 2012 study showed similar protection and overall efficiency estimates with the BAFF On and Off, as well as no relationship between BAFF operation and survival in the Sacramento River and Georgiana Slough. In 2011, the analyses also showed similar protection and overall efficiency rates under both BAFF On and BAFF Off conditions. Additionally, survival estimates for juvenile Chinook salmon observed in both Georgiana Slough and the Sacramento River were similar and not significantly different under BAFF On and BAFF Off conditions. This indicates that the BAFF mode (On/Off) itself does not affect fish survival after contact with the BAFF. Additional discussion on Delta-wide survival is provided below.

- Acoustic telemetry data indicated that predators were located primarily near the river margin, which reduced the rate of encounters with juvenile salmonids that tended to migrate closer to the center of the channel. The relatively low Sacramento River discharges of 2012 may have provided a different bioenergetic landscape than occurred under higher flow conditions in 2011. Additionally, decreased turbidity and increased water temperatures, which are generally associated with lower flow conditions, may have contributed to higher predation rates in 2012 compared to 2011. Estimates of the probability of survival for juvenile salmonids in the river upstream of the BAFF showed higher predation mortality when flows were lower in 2012 compared to the higher flow conditions in 2011.

- It has been hypothesized that a non-physical barrier such as the BAFF may attract predatory fish, thus increasing predation mortality for juvenile salmonids. To examine this hypothesis, predation frequencies were estimated for areas within 5 m of the BAFF and compared to predation rates farther from the BAFF in the Sacramento River. The results do not support the hypothesis that presence of the BAFF increases predation mortality for juvenile salmonids in the immediate vicinity of the non-physical barrier. The similarity between protection and overall efficiency observed in the 2012 studies when the BAFF was on and off supports the findings of the 2011 studies, which showed that one predation event occurred within 5 m of the BAFF and 48 events occurred in the larger array area. It is important to note that if the BAFF were to be used as a long-term management tool, predators could become conditioned to the operation of the BAFF which may allow them to alter their behavior from what was observed in the 2012 and 2011 studies. In addition, the habitat selected by predators and the movement patterns of predators, in the Sacramento River adjacent to the BAFF might vary within and among years in response to factors such as river flow and velocities, water temperatures, turbidity (or clarity), and recreational harvest. These factors, in combination with possible conditioning to

BAFF operations, could result in different predation rates than those observed during the 2012 and 2011 studies.

ES.3.4 2011 DELTA-WIDE SURVIVAL

- The operation of the BAFF did not appear to influence survival of juvenile Chinook below the study area. Survival for the BAFF On and BAFF Off conditions were not significantly different for either route, which suggests that operation of the BAFF did not have a negative effect on survival of fish downstream of the barrier. This finding is not surprising because operation of the BAFF would need to have a large localized effect on survival to considerably influence route-specific survival. Other studies have found an influence of behavioral stimuli on physiological responses of fish, which might in turn affect predation rates. Richards et al. (2007) reported increased cortisol levels in Chinook salmon when the fish were exposed to high-frequency strobe lights, but cortisol levels returned to normal several hours after the stimulus was removed. Flamarique et al. (2006) found that strobe lights could induce torpor in sockeye salmon (*Oncorhynchus nerka*). If excessive stress or torpor was induced by the BAFF, the study team would expect greater mortality for fish that encountered the BAFF in the on state, but such an effect was not observed.

- Survival estimates for fish migrating through the Sacramento River in 2011 under BAFF On and BAFF Off were 0.610 and 0.614, respectively, and estimates for fish migrating through Georgiana Slough were 0.137 and 0.169, respectively (BAFF On/BAFF Off). Estimates for the Sacramento River (0.610 and 0.614) are higher than estimates from Perry et al. (2010) (0.443 to 0.564) and Perry et al. (2012) (0.485 to 0.584). Conversely, the study team's estimates for fish migrating through Georgiana Slough under BAFF On and BAFF Off (0.137 and 0.169, respectively) are lower than estimates by Perry et al. (2010) (0.332 to 0.344) and Perry et al. (2012) (0.179 to 0.314). It is important to note that even with relatively quick travel times, the travel times for a portion of fish moving through both migration routes exceeded estimated tag life. Therefore, the survival estimates provided are likely to be negatively biased.

- Based on these results, with BAFF On, overall survival is (0.926*0.61) + (0.074*0.137) = 0.575. With BAFF Off, overall survival is (0.779*0.614) + (0.221*0.169) = 0.512. This is an 11% relative improvement, not accounting for tag life differences. This addresses the issue noted by Perry et al. (2013), i.e., that changing routing only gives a modest change in survival if reach-specific survivals are not also changed (or different) between the routes.

ES.4 STUDY CONCLUSIONS

The results of the 2012 tests showed that when the BAFF was on there was a statistically significant increase in deterrence, protection, and overall efficiency for juvenile Chinook salmon and steelhead; that is, fewer of the tagged Chinook salmon and steelhead migrated into Georgiana Slough when the BAFF was on than when it was off. For example, there was an approximate 52% reduction in entrainment into Georgiana Slough when the BAFF was on (11.8%) compared to when it was off (24.4%) for juvenile Chinook salmon in 2012, with a similar reduction (approximately 55%) observed for steelhead when the BAFF was on (10.5%) and when it was off (23.4%). The reduction in the probability that juvenile salmonids would migrate into Georgiana Slough was similar in the 2011 studies. The cross-sectional location of fish in the Sacramento River channel when migrating past Georgiana Slough, river flow (and associated physical variables, e.g., water temperature, turbidity), and BAFF operation were found to be important factors influencing the probability that a juvenile Chinook salmon or steelhead would migrate from the Sacramento River into Georgiana Slough during both the 2012 and 2011 studies. Overall, based on a variety of alternative methods and metrics for data analysis, the results of the studies conducted in 2012 and 2011 over a range of Sacramento River flow conditions consistently showed that operation of the BAFF contributed to a reduction in the migration of juvenile salmonids into Georgiana Slough. It is concluded that operation of the BAFF would be likely to result in an incremental increase in through-Delta survival of emigrating Sacramento River juvenile salmonids. The study design for the 2012 and 2011 tests did not include acoustic tag monitoring downstream at Chipps Island or the Golden Gate; therefore, the contribution of operating the BAFF to juvenile salmonid survival through these reaches could not be estimated.

ES.5 RECOMMENDATIONS AND FUTURE DIRECTIONS

It is recommended that the results of the 2012 and 2011 studies, and expected performance of the BAFF in increasing juvenile salmonid survival, be evaluated in context with a lifecycle population dynamics model and/or Delta passage survival model. NMFS is developing a lifecycle model for Sacramento River winter-run Chinook salmon that could potentially be used to assess the incremental contribution of a reduction in juvenile salmon migration into the interior Delta. In addition, the Delta Passage Model (DPM) is used to assess the effects of changes in water project operation and hydrodynamics on survival of juvenile Chinook salmon migrating through the lower Sacramento River and Delta. The lifecycle model could be used to assess the effectiveness of BAFF operations in reducing the risk of incidental take of juvenile salmonids at the south Delta export facilities. It also could be used to assess the incremental contribution of operating the BAFF to the survival and abundance of Chinook salmon. Modeling (e.g., DPM) would also allow an assessment of the BAFF's contributions to increasing juvenile salmonid survival during emigration from the Sacramento River, and the population benefits of improved guidance and reduced mortality on juvenile salmonids. Finally, lifecycle modeling could determine whether the BAFF might contribute, and to what extent it might contribute, to increased adult abundance, species protection, and recovery of listed Sacramento River Chinook salmon and Central Valley steelhead populations. Efforts are also underway to conduct additional studies on the route selection, survival, risk of predation, and response to tidal and hydrodynamic conditions of juvenile salmonids. These studies are intended to complement and support additional testing and analysis of the biological benefits to salmon and steelhead from management actions such as those undertaken at Georgiana Slough.

Based on the extensive body of information developed through the 2012 and 2011 studies, it is recommended that no additional BAFF testing be conducted at Georgiana Slough using the barrier configuration tested in 2012 and 2011. Results of the 2 years of study, in combination with statistical and simulation models that have been developed, could be used to refine and optimize the BAFF configuration and location, which would be subject to additional testing. Operation of the BAFF contributed to reduced entrainment into Georgiana Slough in both 2012 (during lower flow conditions) and 2011 (during high-flow conditions). However, the capital, operating, and maintenance costs of the BAFF are relatively high; installation and maintenance can be difficult during high flow conditions; the BAFF is a complex facility requiring substantial staff resources for operations; and reliable operation under variable conditions inherent in the Sacramento River should be carefully evaluated before a permanent installation is considered.

As an alternative to the BAFF, it is recommended that consideration be given to testing a floating fish guidance fence (floating boom-type structure) in 2014 (possibly in combination with an optimized BAFF configuration and operation). Like the BAFF, it would be used to prevent juvenile salmonids in the Sacramento River from entering

Georgiana Slough. Similar fish guidance systems have been tested and proven to be effective for juvenile salmonids in other West Coast river systems. Results of both the 2012 and 2011 tests are consistent in showing that relatively small changes in the cross-sectional location of juvenile salmonids in the Sacramento River channel upstream of Georgiana Slough could contribute to substantial reductions in the risk that juvenile Chinook salmon and steelhead will migrate from the Sacramento River into the interior Delta via Georgiana Slough.

1 INTRODUCTION

1.1 BACKGROUND

The Sacramento River and its tributaries support populations of anadromous fish species/races, including winter-run, spring-run, fall-run, and late fall-run Chinook salmon (*Oncorhynchus tshawytscha*), and steelhead (*O. mykiss*). Several of these species/races are listed as threatened or endangered under the California Endangered Species Act, federal Endangered Species Act (ESA), or both. Adult salmon and steelhead use the Sacramento River primarily as a migration corridor to access spawning grounds in the upper Sacramento River watershed. Juvenile Chinook salmon and steelhead migrate downstream in the Sacramento River from their natal streams into the Sacramento-San Joaquin Delta (Delta) on their journey to the Pacific Ocean over the winter and spring period. During their migration, juvenile salmonids encounter alternative migration pathways through the Delta other than the mainstem Sacramento River. These alternative migration pathways are all distributaries of the Sacramento River and include the Sutter/Steamboat sloughs route, the Delta Cross Channel (DCC)/North and South forks of the Mokelumne River route, the Georgiana Slough route, and the Threemile Slough route.

Results of experimental survival studies have demonstrated substantially higher mortality rates for juvenile salmon that attempt to migrate through the interior Delta via the DCC or Georgiana Slough routes when compared to fish that remain in the mainstem Sacramento River (Brandes and McLain 2001; Perry 2010). Studies of juvenile Chinook salmon migration have shown losses (i.e., mortality) of approximately 65 percent of the outmigrating fish that leave the mainstream Sacramento River and migrate via other waterways of the central and south Delta (Perry 2010; Perry et al. 2010; Perry et al. 2012; Perry et al. 2013). Movement of these fish into the interior and south Delta increases the likelihood of losses through predation, entrainment into in-Delta diversions, and mortality associated with the State Water Project (SWP) and Central Valley Project (CVP) pumping facilities in the south Delta (Perry 2010; NMFS 2009). **Figure 1-1** shows the migration pathways in the lower Sacramento River/north Delta for outmigrating juvenile salmonids, the location of the DCC, and the SWP and CVP pumping facilities in the south Delta.

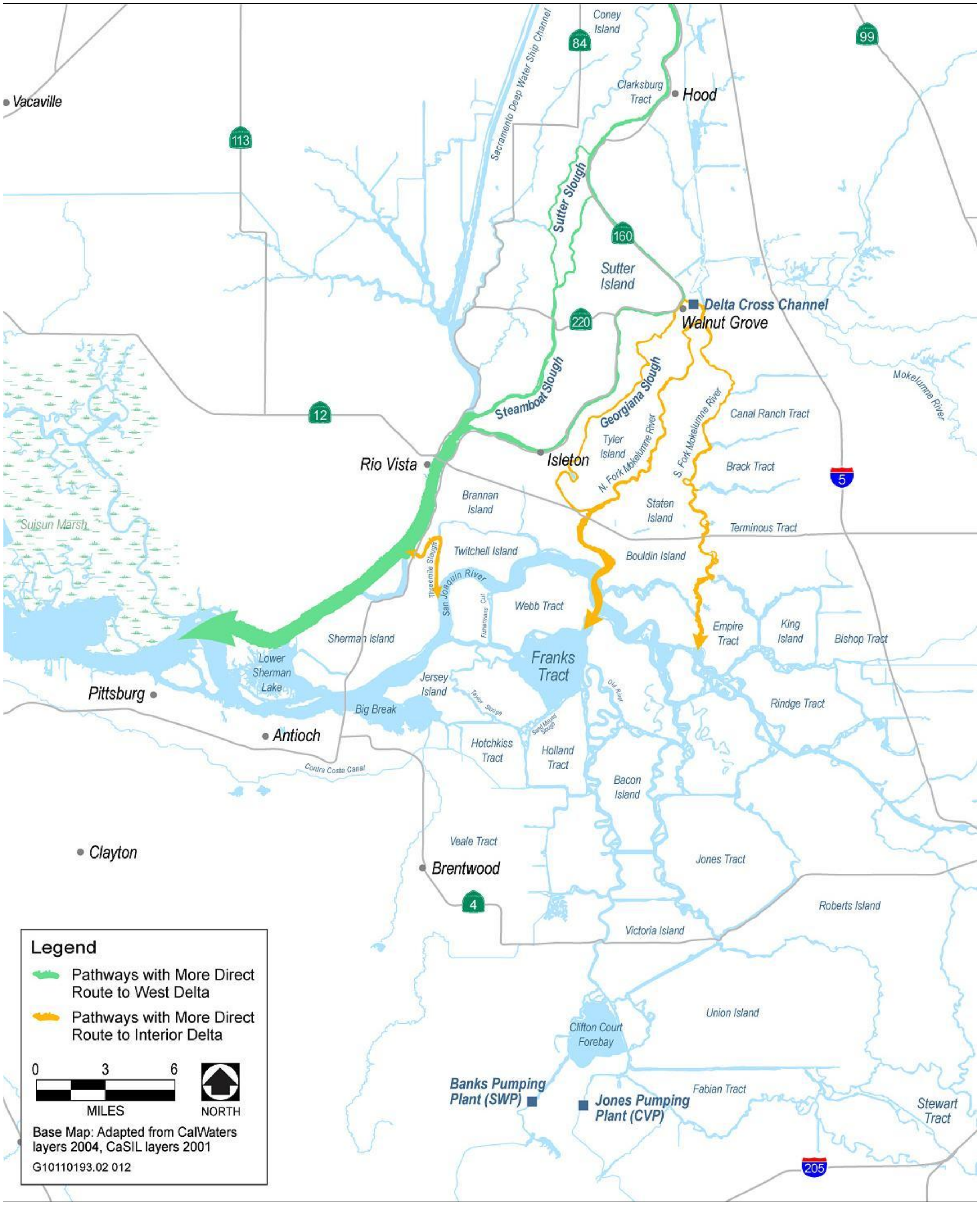
Passage of juvenile salmonids from the Sacramento River into the interior Delta through the DCC can be reduced by closing the radial gates at the head of the facility from mid-December through May. When closed, the gates create a physical barrier to flows, fish, and boats. No similar protection is available to reduce the movement of juvenile salmonids from the Sacramento River into the interior Delta via Georgiana Slough. Flows into Georgiana Slough improve water quality by reducing salinity in the interior Delta, and the absence of a physical barrier provides unrestricted access for recreational boaters. Because of these benefits, alternatives to a physical barrier are being investigated. Consideration has been given to using a non-physical barrier at the divergence of Georgiana Slough from the Sacramento River. Use of a non-physical barrier could potentially reduce the movement of juvenile salmonids into Georgiana Slough and thereby improve their survival rate without reducing flows into the slough. In 1994, several experiments were conducted to evaluate the potential effectiveness of an acoustic barrier (underwater sound) in preventing migrating juvenile salmonids from entering the slough. A Kodiak trawl was used in both the Sacramento River and Georgiana Slough when the barrier was "on" (i.e., in operation) and when it was "off" to capture juvenile Chinook salmon. The relative numbers of fish captured under different operating scenarios were then used to quantify the efficiency of the barrier in guiding fish to remain the in Sacramento River. Overall, the barrier guidance efficiency averaged 57 percent (95 percent confidence interval [CI] 47–65 percent) and was statistically significant ($p<0.001$) (SLDMWA and Hanson 1996).

Guidance efficiency was found to be greater during ebb tide (62 percent) than during flood tide (51 percent) and greater during the daytime than at night. Because the guidance efficiency observed in the 1994 tests was less than the 95 percent level of performance assumed for a non-physical barrier, testing of the acoustic barrier was discontinued.

Subsequent to the foregoing acoustic barrier tests, substantial research and development have been directed toward improving the effectiveness of non-physical barriers in guiding juvenile salmonids and other fish species. Testing has led Fish Guidance Systems of Southampton, United Kingdom, to develop a non-physical barrier, referred to as a behavioral Bio-Acoustic Fish Fence™ (BAFF), that combines three stimuli to deter the movement of juvenile salmonids: sound, high intensity modulated light (HIML) (previously described as stroboscopic light), and an air bubble curtain. Testing of a BAFF in Europe has produced promising results (Welton et al. 2002; Turnpenny and O'Keefe 2005; Beaumont, pers. comm., 2011).

In 2009, a BAFF was tested in the San Joaquin River to determine its efficiency in guiding juvenile Chinook salmon migrating downstream where they encountered the divergence of Old River from the San Joaquin River at the Head of Old River (HOR) (Bowen et al. 2012). The testing results showed that a statistically significant proportion of juvenile Chinook salmon was deterred from entering Old River (81 percent deterrence rate). Mortality losses (assumed to be due to predation), however, were high both upstream and in the vicinity of the barrier. The results of similar tests conducted in spring 2010 (Bowen and Bark 2012) showed that deterrence efficiency (i.e., the change in the proportion of juvenile Chinook salmon that are deterred when the barrier is on, compared to when the barrier is off) increased from approximately 5 percent when the barrier was off to 23 percent when the barrier was on, an improvement of 17 percentage points. Protection efficiency (i.e., the change in the proportion of juvenile Chinook salmon that survive to HOR and pass downstream from the HOR when the barrier is on, compared to when the barrier is off) increased from 26 percent when the barrier was off to 43 percent when the barrier was on, an improvement of 17 percentage points, during the 2010 tests. The results of these tests indicated that the BAFF showed promise as a non-physical barrier that could provide significant positive guidance of juvenile Chinook salmon.

Under the federal ESA, the National Marine Fisheries Service (NMFS) issued the 2009 *Biological and Conference Opinion for the Long-Term Operations of the Central Valley Project and State Water Project* (BiOp) for Chinook salmon and other listed anadromous fish (NMFS 2009). Reasonable and Prudent Alternative (RPA) Action IV.1.3 of the BiOp requires the California Department of Water Resources (DWR) and U.S. Bureau of Reclamation (Reclamation) to consider engineering solutions to reduce the diversion of juvenile salmonids from the Sacramento River into the interior and south Delta. Based on past test results showing the effectiveness of a BAFF, DWR designed and implemented the 2011 Georgiana Slough Non-Physical Barrier (GSNPB) Study to evaluate the effectiveness of using a BAFF to prevent outmigrating juvenile Chinook salmon from entering Georgiana Slough.



Source: AECOM 2013

Figure 1-1 **Lower Sacramento River/North Delta Migration Pathways**

In 2011, a BAFF was tested in the Sacramento River to determine its efficiency in guiding juvenile Chinook salmon migrating downstream where they encounter the junction with Georgiana Slough (DWR 2012). The 2011 test results showed that a statistically significant proportion of juvenile Chinook salmon was deterred from entering Georgiana Slough. During the 2011 study period, the non-physical barrier reduced the percentage of juvenile Chinook salmon passing into Georgiana Slough from 22.1 percent (BAFF Off) to 7.4 percent (BAFF On), a reduction of two-thirds of the fish that would have been otherwise entrained into Georgiana Slough. This improvement produced an overall efficiency rate of 90.8 percent. In other words, 90.8 percent of juvenile Chinook salmon that entered the study area when the BAFF was on continued down the Sacramento River. Three metrics of BAFF performance—deterrence, protection, and overall efficiency—were estimated from the results of the 2011 studies to compare passage of juvenile Chinook salmon into Georgiana Slough when the BAFF was on and when it was off. Based on all three metrics, barrier efficiency was significantly higher when the BAFF was on relative to periods when the BAFF was off. Based on the similarity between estimates of protection and overall efficiency, the effects of predation on juvenile Chinook salmon in the study area were low. Furthermore, analysis of the 2011 study results using a generalized linear model (GLM) found that river discharge, which is a function of velocity, the cross-sectional location of the fish in the Sacramento River, and BAFF operations, were important predictors of fish behavioral response to the BAFF and entrainment into Georgiana Slough. It is hypothesized that high flows in the Sacramento River and corresponding increased water velocities and turbidity levels may have contributed to the relatively low level of predation on juvenile Chinook salmon estimated during the 2011 tests. Overall, the results of the 2011 tests indicated that the BAFF showed promise as a barrier that could provide significant positive guidance of juvenile Chinook salmon. The 2012 GSNPB Study represents the second year of BAFF performance evaluation at the divergence of Georgiana Slough from the Sacramento River.

1.2 STUDY PURPOSE, OBJECTIVES, AND OVERVIEW

The primary purpose of the 2012 GSNPB Study was to further test the effectiveness of a BAFF in preventing outmigrating juvenile Chinook salmon and steelhead from entering Georgiana Slough.

The objectives of the 2012 GSNPB Study were:

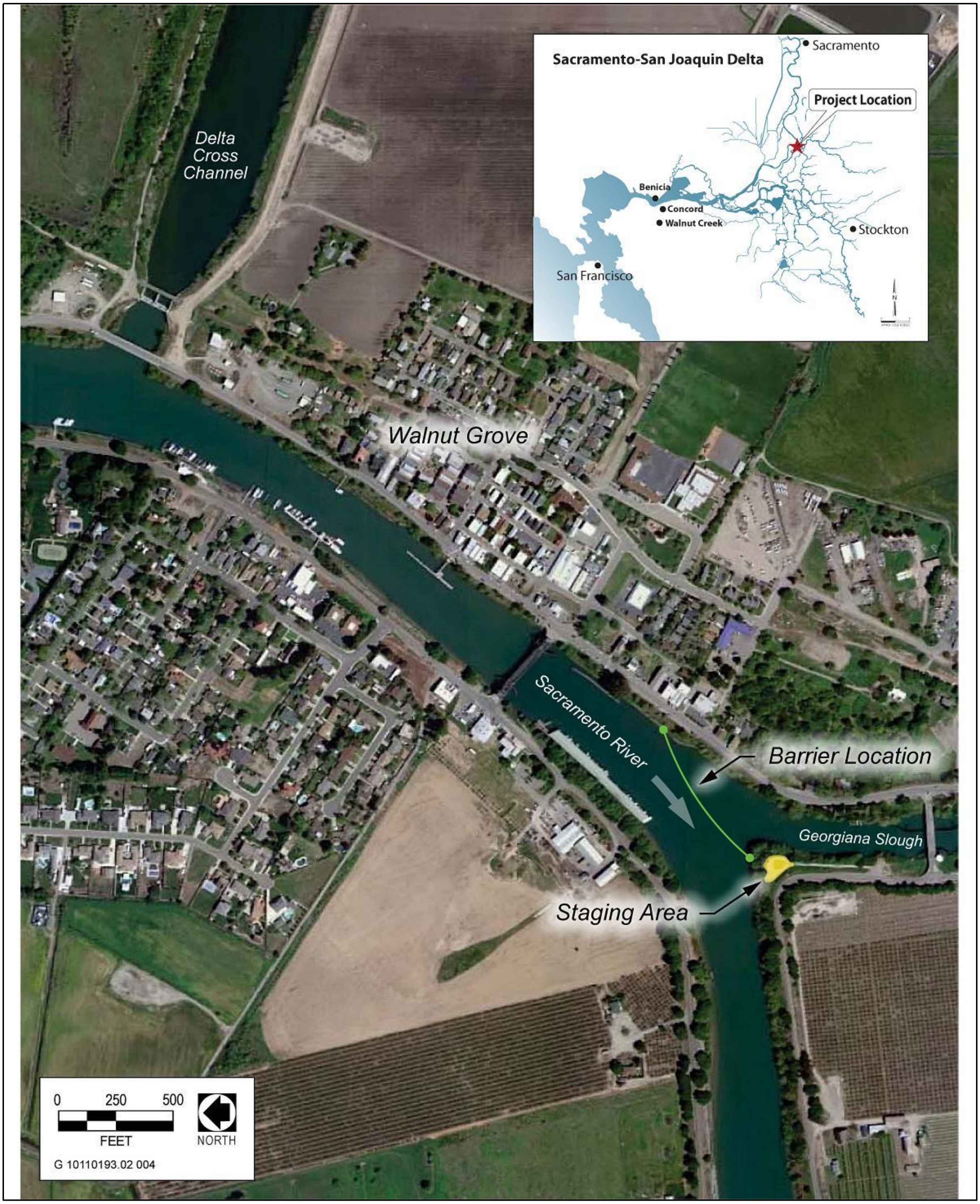
- to estimate the effectiveness of the BAFF in successfully deterring juvenile Chinook salmon and steelhead from entering Georgiana Slough and guiding them to continue their migration downstream in the Sacramento River;
- to determine the relative contribution of various physical factors, such as the status of the BAFF (on or off), water velocity, ambient light, and location of fish in the channel cross-section in the Sacramento River on the effectiveness of the BAFF; and
- to examine the behavior, movement, and response of predatory fish, such as striped bass (*Morone saxatilis*), near the BAFF, and develop estimates of predation on juvenile salmonid.

The experimental tests conducted as part of the 2012 GSNPB Study provided additional data to support the feasibility study and field testing required under RPA Action IV.1.3 of the NMFS BiOp. Both the 2011 and the 2012 GSNPB studies were designed to assist DWR and Reclamation in meeting required actions for SWP and CVP compliance with the ESA and the NMFS BiOp. They also were designed to assist with informing decision making and adaptive management of the NMFS BiOp RPA actions, which could contribute to reducing adverse impacts on ESA-listed anadromous salmonids associated with long-term SWP and CVP operations.

The 2012 tests involved releasing juvenile late fall-run Chinook salmon and steelhead, reared at the Coleman National Fish Hatchery that were implanted with acoustic transmitters, into the Sacramento River immediately downstream from Steamboat Slough, approximately 8.9 kilometers (km) upstream from Georgiana Slough. Each fish had an acoustic tag with a unique code. The tests involved tracking the study fish movements to determine the proportion of tagged fish that entered the study area and successfully migrated downstream via the Sacramento River when the barrier was on and when it was off, and the proportion that migrated via Georgiana Slough when the barrier was on and when it was off. **Figure 1-2** shows the study location, and **Figure 1-3** shows the conceptual design of the BAFF used at Georgiana Slough.

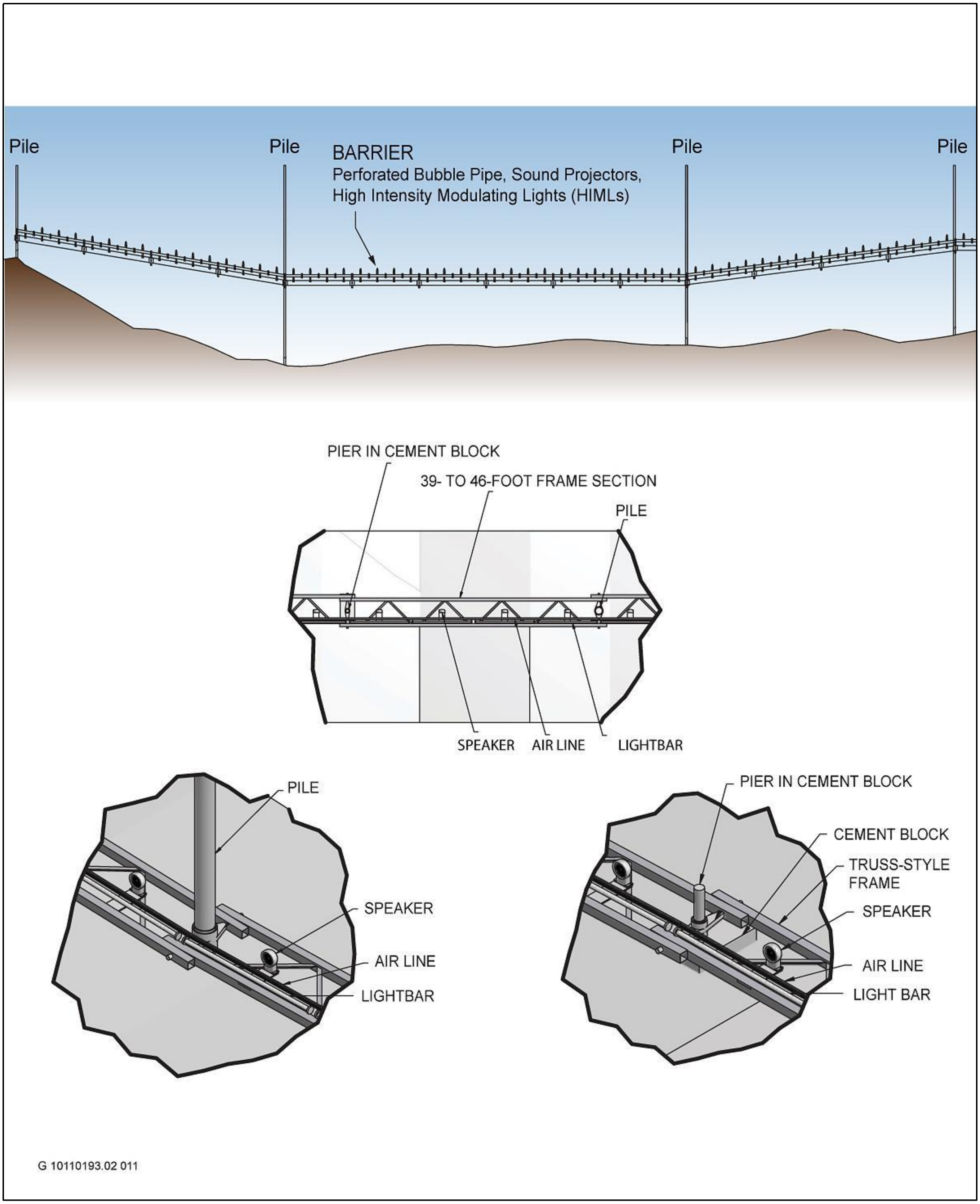
As part of the 2012 tests, striped bass and other predatory fish were also implanted with acoustic transmitters and monitored to determine the behavior and movement patterns of predatory fish in response to environmental conditions, and the potential for salmon predation by the tagged predatory fish in association with operations of the non-physical barrier.

The experimental design of the study was developed to provide information on the behavioral response of juvenile Chinook salmon and steelhead encountering the BAFF over a range of environmental conditions (e.g., tidal conditions, day and night (i.e., light), Sacramento River flows and water velocity, rate of flow entering Georgiana Slough). This information was valuable in determining the barrier's overall effectiveness across a range of conditions and provided a technical foundation for future refinements to the design and installation of a non-physical barrier. The statistical power of the experimental design was maximized through the use of continuous monitoring of flow velocity and day/night conditions immediately upstream from the barrier location. Continuous monitoring allowed the range of conditions likely to affect the movement and fate of tagged juvenile salmonids entering the study area to be recorded and documented. Results of the 2012 and 2011 tests provide the basis for statistical models that can be used to evaluate how various environmental factors influence the barrier's performance in deterring fish from entering Georgiana Slough. The 2012 and 2011 test results also provide a strong technical basis for assessing the performance of the BAFF, as well as a statistical basis for refining and improving the experimental design of any subsequent tests.



Source: Data provided by California Department of Water Resources and adapted by AECOM in 2012

Figure 1-2 **Location of 2012 Georgiana Slough Non-Physical Barrier Study**



Source: Data provided by Fish Guidance Systems and adapted by AECOM in 2012

Figure 1-3 **Conceptual Design of the 2012 BAFF Used at Georgiana Slough**

1.3 ORGANIZATION OF THE REPORT

This 2012 GSNPB Performance Evaluation Project Report is organized as follows:

- Chapter 1, "Introduction," provides a summary background on anadromous salmonid outmigration in the Sacramento River, including route selection and survival; summarizes past studies of behavioral fish barriers; and describes the study purpose, objectives, and overview.
- Chapter 2, "Experimental Design and Implementation," provides an overview of the experimental design and describes in detail the different components associated with the experiment implementation.
- Chapter 3, "Analysis Methods, Results, and Discussion," describes the methods, results, and discussion of the different analyses conducted as part of the overall project. The different analyses are presented in the following sections:
  - Section 3.1, "Fish Track Processing and Development";
  - Section 3.2, "Barrier Deterrence, Protection, and Overall Efficiency";
  - Section 3.3, "Survival and Route Entrainment Probabilities";
  - Section 3.4, "Hydrodynamics and Critical Streakline Analysis";
  - Section 3.5, "Spatial Analysis of Fish Distribution and Behavior";
  - Section 3.6, "Generalized Linear Modeling of Tagged Fish Fates";
  - Section 3.7, "Analysis of Predators and Predation"; and
  - Section 3.8, "2011 GSNPB Delta-wide Survival."
- Chapter 4, "Integration and Synthesis of Results," provides a summary integration and synthesis of the results from the different analyses, especially those related directly to the barrier performance evaluation. This chapter also provides a summary comparison of the 2011 and 2012 study results.
- Chapter 5, "Summary of Key Findings and Conclusions," highlights the key findings and conclusions of the study.
- Chapter 6, "Recommendations and Future Directions," provides a suite of management-level recommendations.
- Chapter 7, "References," identifies the sources of information cited in this report.
- Appendix A, "2012 GSNPB Acoustic Tag System Data Collection Plan," describes the data collection plan for the acoustic tag and detection system.
- Appendix B, "2012 GSNPB Study Fish Summary Statistics," presents summary statistics on the study fish (tagged Chinook salmon and steelhead).
- Appendix C, "2012 GSNPB Summary of Standard Operating Procedures," provides a summary of the different standard operating procedures that were developed and used during study implementation and data collection.

- Appendix D, “2012 GSNPB Fish Tagging Effects Study,” presents methods and results from the fish health study that was implemented to assess tagging effects on study fish.
- Appendix E, “2012 GSNPB Fish Track Processing and Development Comparison,” presents methods and results from two different fish track processing and development procedures.
- Appendix F, “On the Hydrodynamics of Entrainment of Juvenile Salmon in Tidally Forced Junctions, Georgiana Slough: A Case Study,” presents methods and results from analysis of hydrodynamics and entrainment of juvenile salmon at the Georgiana Slough junction.
- Appendix G, “Determinations of Over-Barrier or Under-Barrier Passage of Acoustically Tagged Fish,” presents methods and results of determining whether tagged fish passed over or under the non-physical barrier.
- Appendix H, “Analyses of Tagged Fish Released by the Sacramento Regional County Sanitation District,” presents methods and results of analyses of tagged fish released by the Sacramento Regional County Sanitation District during the 2012 GSNPB Study.

This page intentionally left blank.

2 EXPERIMENTAL DESIGN AND IMPLEMENTATION

2.1 OVERVIEW OF EXPERIMENTAL DESIGN

The overall goal of implementing a barrier at this location is to reduce the migration of juvenile anadromous salmonids into the interior Delta through Georgiana Slough where they are less likely to survive and their vulnerability to entrainment into the SWP and CVP south Delta export facilities is greater (Perry 2010). Like the 2011 study design, the overall objective of the 2012 design was to provide for the effective release, monitoring and documenting of the response of fish encountering the Sacramento River and Georgiana Slough divergence when the BAFF was on and off under a range of environmental conditions.

The 2012 GSNPB Study experimental design was based on the 2011 design and information gathered during the 2011 testing. The basic 2012 GSNPB Study design concept matched the 2011 concept including: BAFF alignment; use of in-water monitoring equipment including hydrophones, acoustic Doppler current profilers (ADCP), and a Dual frequency IDentification SONar (DIDSON) camera; the surgical implanting of acoustic tags and release of hatchery-raised juvenile late fall-run Chinook salmon and steelhead into the Sacramento River immediately downstream from Steamboat Slough; the surgical implanting of acoustic tags and release of wild predatory fish upstream of the barrier; the monitoring and comparison of the proportion of tagged fish (salmon and steelhead) entering the study area that successfully migrated downstream via the Sacramento River when the barrier was on to the proportion that migrated via Georgiana Slough when the barrier was off; and the monitoring of tagged predator behavior. Differences from the 2011 study design included: additional tagging and release of steelhead; inclusion of hydroacoustic transducers for monitoring untagged wild predator movements; incorporation of pile-mounted floating buoys to support near-barrier hydrophones; and orientation of these same hydrophones to be outward-looking instead of upward-looking.

2.2 KEY COMPONENTS OF 2012 EXPERIMENTAL TESTS

The 2012 GSNPB Study included the following key components:

- A total of 1,501 late fall–run Chinook salmon and 299 steelhead produced at the Coleman National Fish Hatchery were acoustically tagged with acoustic transmitters and released into the Sacramento River, and their downstream migration past the BAFF and Georgiana Slough was monitored.
    - Fish were released from March 6, 2012, through April 23, 2012, during an important migratory period for salmonids.
    - Releases into the Sacramento River were made approximately 8.9 km upstream from the BAFF to maximize the number of fish that encounter the barrier while also allowing the fish time to adjust to the river conditions and disperse into the channel before encountering Georgiana Slough.
    - Passage of tagged Chinook salmon and steelhead was monitored at and downstream from the BAFF in the Sacramento River and Georgiana Slough both when the barrier was on and when it was off.

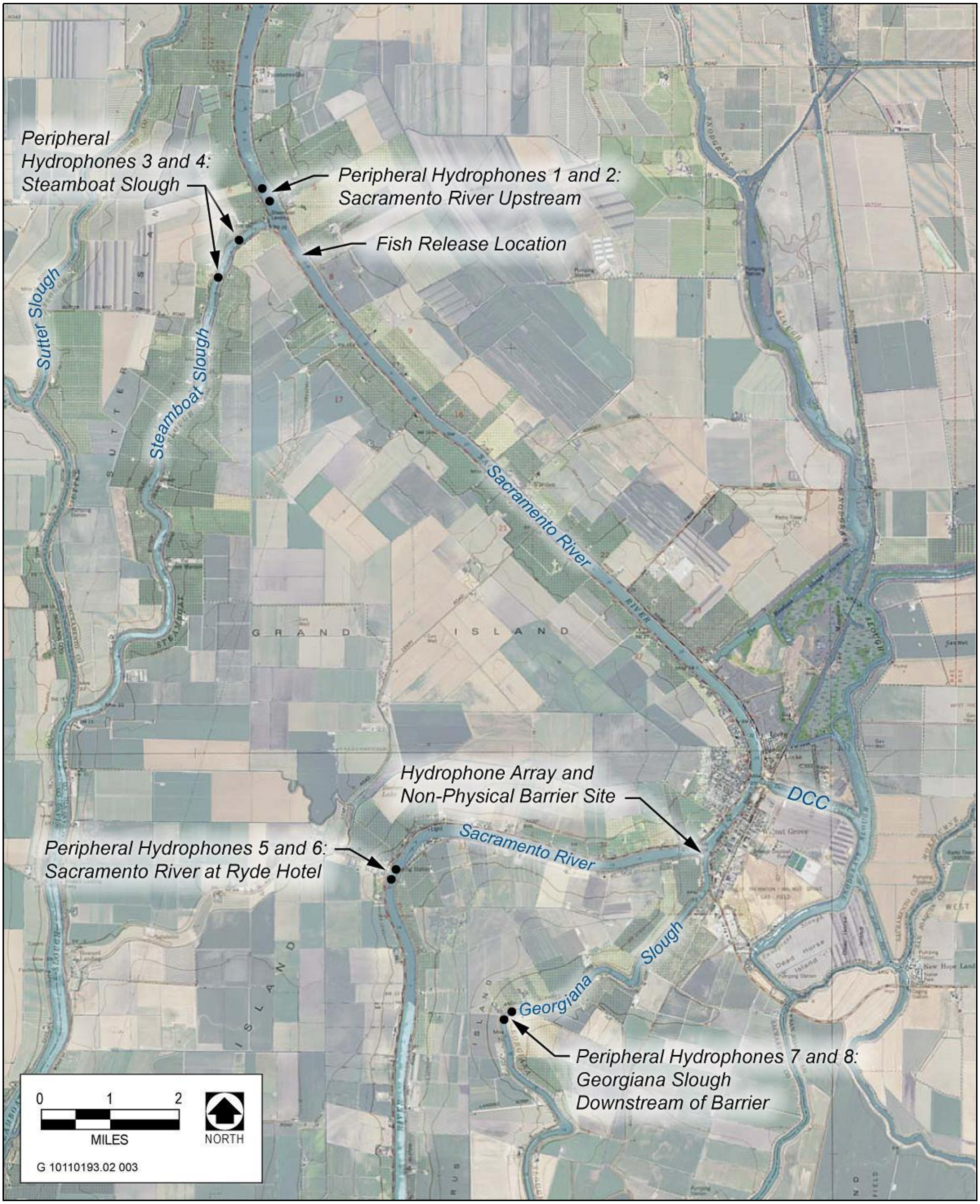
- Several species of predatory fish were captured, implanted with acoustic tags, released, and monitored to evaluate behavior, movement patterns, and potential predation of tagged juvenile Chinook salmon and steelhead in association with the presence and operations of the BAFF.

- Multiple hydrophones were installed in the Sacramento River immediately upstream from, downstream from, and adjacent to the barrier to monitor movements of tagged fish as they encountered and responded to the barrier. These hydrophones are referred to as the array at the barrier or study array. The study array allowed for three-dimensional positioning of tagged fish. The pathway of each tagged fish, over or under the BAFF, was determined for each tag that crossed the BAFF alignment. Additional hydrophones, referred to as the peripheral hydrophones, were installed to detect tagged fish in channels upstream and downstream from the study array.

- Multiple ADCPs were installed in the Sacramento River in the vicinity of the barrier to monitor local currents, water velocities, and general hydrodynamics.

- Active multibeam hydroacoustic devices, including a DIDSON camera were installed to monitor fish densities in the immediate vicinity of the BAFF.

Figure 2-1 provides an overview of the study area, including the release location for tagged late fall-run Chinook salmon and steelhead; the location of the BAFF; and the locations of the acoustic tag detection and monitoring systems.



Source: Data provided by California Department of Water Resources and adapted by AECOM in 2012

Figure 2-1 **Overview of the 2012 Georgiana Slough Non-Physical Barrier Study Area**

2.3 HYPOTHESIS TESTING OF BARRIER EFFICIENCY

As previously noted, the 2012 GSNPB Study was designed to test the BAFF's performance by testing deterrence efficiency, protection efficiency, and overall efficiency. The hypotheses related to each of these evaluation metrics of barrier efficiency are described next.

2.3.1 DETERRENCE EFFICIENCY

Determining the efficiency of the BAFF in deterring juvenile Chinook salmon and steelhead from entering Georgiana Slough was an important evaluation metric. To determine deterrence efficiency, the change in the proportion of tagged fish migrating downstream in the Sacramento River when the barrier was on was compared to the proportion migrating downstream when the barrier was off.

The BAFF's deterrence efficiency was calculated as:

$$D = B/(B+C)$$

where:

D = deterrence efficiency,

B = the number of juvenile salmonids deterred by the barrier (i.e., approaching within 80 meters (m) of the barrier and visibly changing direction by making a directed movement away from the BAFF), and

C = the number of juvenile salmonids approaching within 80 m of the barrier and undeterred by the barrier.

The following *null hypothesis* was tested for the deterrence efficiency of the BAFF:

$H1_o$: There is no statistically significant difference in the proportion of tagged juvenile Chinook salmon or steelhead that is deterred from entering Georgiana Slough upon approach within 80 m of the BAFF when the BAFF is on compared to when the BAFF is off.

The following *alternative hypothesis* was tested for the BAFF's deterrence efficiency:

$H1_A$: There is a statistically significant increase in the proportion of juvenile Chinook salmon and steelhead that is deterred from entering Georgiana Slough upon approach within 80 m of the BAFF when the BAFF is on compared to when the BAFF is off (i.e., deterrence efficiency is statistically significantly greater with the barrier on than with the barrier off).

2.3.2 PROTECTION EFFICIENCY

Determining whether operation of the BAFF increased the proportion of juvenile Chinook salmon and steelhead that migrated via the Sacramento River rather than via Georgiana Slough was another important evaluation metric. Defined as protection efficiency, this metric describes the incidence of juvenile Chinook salmon and steelhead successfully migrating downstream via the Sacramento River, as measured by the proportion of tagged Chinook salmon and steelhead detected migrating to a location approximately 3.2 km downstream from the barrier location (relative to the total number of Chinook salmon and steelhead migrating down the Sacramento River and Georgiana Slough combined).

The BAFF's protection efficiency was calculated as:

$$P = F/(F+G)$$

where:

P = protection efficiency,

F = the number of juvenile salmonids that pass the downstream Sacramento River tag detection site (or peripheral node) (i.e., Hydrophones 5 and 6), and

G = the number of juvenile salmonids that pass the downstream Georgiana Slough tag detection site (or peripheral node) (i.e., Hydrophones 7 and 8).

All tagged juvenile Chinook salmon and steelhead that were determined to have been consumed by predators in the study array were excluded from the calculation of protection efficiency. Thus, protection efficiency is a measure of the proportion of only juvenile Chinook salmon or steelhead moving downstream in the Sacramento River (not in Georgiana Slough) (i.e., it is a measure of routing alone).

The downstream monitoring locations (one pair of hydrophones each in both the Sacramento River and Georgiana Slough downstream from the array) were selected because they were sufficiently distant from the BAFF to ensure that juvenile Chinook salmon and steelhead were completely out of the barrier's potential area of influence and free from any associated increased risk of predation mortality associated with the BAFF's infrastructure. Additionally, the downstream monitoring locations represent a distance of greater than one tidal excursion from the barrier.

The following *null hypothesis* was tested for the protection efficiency of the BAFF:

$H2_o$: There is no statistically significant difference in the proportion of tagged juvenile Chinook salmon and steelhead that migrate approximately 3.2 km down the Sacramento River when the BAFF is on compared to when the BAFF is off.

The following *alternative hypothesis* was tested for the BAFF's protection efficiency:

$H2_A$: There is a statistically significant increase in the proportion of juvenile Chinook salmon and steelhead that migrate approximately 3.2 km down the Sacramento River when the BAFF is on compared to when the BAFF is off (i.e., protection efficiency is statistically significantly greater with the barrier on than with the barrier off).

2.3.3 Overall Efficiency

Determining the overall proportion of juvenile Chinook salmon or steelhead entering the study area and successfully migrated downstream in the Sacramento River is another important metric. This metric was defined as overall efficiency. Based on monitoring results that showed the numbers of tagged juvenile Chinook salmon and steelhead entering the study area and those that were subsequently detected successfully migrating downstream via the Sacramento River, hypotheses were tested to determine whether there was a significant difference in the overall proportion of tagged Chinook salmon and steelhead that successfully migrated downstream via the Sacramento River when the BAFF was on relative to periods when the BAFF was off.

The BAFF's overall efficiency was calculated as:

$O = F/E$

where:

O = overall efficiency,

F = the number of juvenile salmonids that pass the downstream Sacramento River tag detection site (or peripheral node) (i.e., Hydrophones 5 and 6), and

E = the number of juvenile salmonids that enter the study area.

All tagged fish that entered the study area and that had fates classified (see Section 2.6.4) were included in the calculation of overall efficiency. As noted previously, to account for predation mortality on juvenile Chinook salmon and steelhead, protection efficiency was calculated to account for only those acoustic tag tracks that were characterized as not having been eaten by a predator (i.e., the tags reached the peripheral hydrophones in the Sacramento River or Georgiana Slough). As a result, comparing protection efficiency with overall efficiency provides an indicator of predation effects on BAFF efficiency. This may include tagged salmon and steelhead that were preyed on by predators after they left the study area and moved downstream.

The following *null hypothesis* was tested for the overall efficiency of the BAFF:

$H3_o$: There is no statistically significant difference in the proportion of tagged juvenile Chinook salmon and steelhead that have been released upstream from the BAFF and successfully migrate downstream via the Sacramento River when the BAFF is on compared to when the BAFF is off.

The following *alternative hypothesis* was tested for the BAFF's overall efficiency:

$H3_A$: There is a statistically significant increase in the proportion of tagged juvenile Chinook salmon and steelhead that have been released upstream from the BAFF and successfully migrate downstream via the Sacramento River when the BAFF is on compared to when the BAFF is off (i.e., overall efficiency is statistically significantly greater with the barrier on than with the barrier off).

2.4 STATISTICAL BASIS AND SAMPLE SIZES FOR THE EXPERIMENTAL DESIGN

Data were analyzed for this study using three principal statistical approaches. In the first approach, hypothesis testing, hypotheses were explicitly stated *a priori* (not based on prior studies), critical alpha values were described, and the analytical conditions for each study division outlined. For the second approach, survival and route entrainment probabilities, a mark-recapture model was developed to predict the probability of route-specific fish survival and route entrainment in relation to barrier operation. For the third approach, GLM, modeling was used to examine the importance of barrier operation (relative to other independent variables) in influencing whether: juvenile Chinook salmon and steelhead continue migrating via the Sacramento River or they migrate via Georgiana Slough.

Evidence suggests that the movement and fate of juvenile Chinook salmon and steelhead are affected by a minimum of three generalized variables: day/night phase (light), Sacramento River discharge, and tidal phase

(Blake and Horn 2006; Horn and Blake 2004; Perry 2010; Chapman et al. 2013). Day/night phase and discharge are important drivers; ultimately, however, the varying combinations of light, velocity, and velocity direction created by these variables are important factors that may influence the performance of the BAFF. To take these variables into account, underwater light levels and water velocities were considered. The water velocity variables consisted of along-barrier velocity, cross-barrier velocity, and upstream secondary circulation (and its influence on fish position), along with a normalized combination of these variables. Independent variables (light and velocity) were partitioned into two categories (high and low) based on statistical and biological considerations. The effectiveness of the BAFF (evaluated through calculation of deterrence, protection, and overall efficiencies) was tested using different combinations of light and velocity high/low categories. Additional variables, including study fish size and water quality parameters, were also considered in the analysis (see Section 3.2).

For the hypothesis testing, a single "sample" was defined as a period during which: 1) the BAFF On/Off state did not change; 2) light did not cross a threshold level; and 3) velocity did not cross a threshold level. Additional discussions on light and velocity threshold levels are provided in Section 3.2. All tagged fish that passed the BAFF during a single sample period were used to calculate the deterrence, protection, and overall efficiency for that sample. Null hypotheses $H1_0$, $H2_0$, and $H3_0$ (described in Section 2.2, "Hypothesis Testing of Barrier Efficiency") were tested without dividing the samples into light-velocity combinations. That is, all samples were combined into simple BAFF On versus BAFF Off comparisons.

The null hypotheses ($H1_0$, $H2_0$, and $H3_0$) were also tested for each of the unique combinations of light and velocity categories previously described. All samples were categorized into light and velocity categories, and for each light category, the three null hypotheses were tested. The three null hypotheses were also tested for each velocity category. In addition to this univariate hypothesis testing approach, an exploratory approach based on combining multiple independent variables in a GLM was also used, similar to the approach used by Perry (2010). The results of two years of the HOR study and one year of the GSNPB Study (2011) conducted by DWR have suggested that several variables not included in the hypothesis testing framework described previously may influence fish behavior and barrier effectiveness. Ultimately, the GLM analysis was directed toward answering the following question: After accounting for other independent variables, does the operation of the barrier significantly increase the probability that a tagged fish will pass down the Sacramento River rather than down Georgiana Slough? The GLM provides insight into the relative importance of different independent variables (including barrier operation) in influencing passage of tagged fish down the Sacramento River. Descriptions of the estimation and statistical testing methods used for hypothesis testing and GLM are provided in sections 3.2 and 3.4, respectively.

A power analysis based on the results of two years of the HOR study and one year of the GSNPB Study (2011) was used to calculate the minimum number of test fish for the study. The analysis considered agreed upon confidence levels to detect a percent change in each study hypotheses for the barrier on and off states over the expected range of environmental conditions. For the 2011 GSNPB Study, it was not known how many test fish might be consumed by predators in the study area or before reaching the study area. Releases of tagged juvenile late fall-run Chinook salmon modeled by Perry (2010) reported that 88–93 percent of fish survived passage from immediately downstream from Steamboat Slough to immediately upstream from the DCC. However, these fish were released at river mile 57 (approximately 37 km upstream from Steamboat Slough) and had more time to acclimate to riverine conditions than fish released just below the mouth of Steamboat Slough, as implemented in the 2011 and 2012 GSNPB studies. Based on the results of prior tests in the Sacramento River (Perry 2010), it was estimated that mortality in the reach between Steamboat Slough and the BAFF would be less than 10 percent. Assuming release of about 1,500 tagged Chinook salmon and steelhead over the total test period and less than 10 percent in-river mortality upstream from the barrier, a minimum of 1,350 tagged Chinook salmon and steelhead were expected to enter the study area.

During the entire study period, the study plan was to expose about half of the test fish to the BAFF when it was on and half when the BAFF was off. To accomplish this goal, it was proposed that barrier operation be switched at the end of every 25-hour tidal cycle and that small groups of fish be released every three hours during the 45-day study period. By operating the BAFF in an on/off mode based on a 25-hour tidal cycle, tagged fish were exposed to the full range of barrier, tidal, and diurnal conditions that occurred over the study period.

About four tagged salmonids were released every three hours to expose test fish to the full range of diel periods and tidal conditions that occurred over the March 6 through April 23 release period. Fish were released into the Sacramento River at a location approximately 8.9 km upstream from the BAFF to allow the fish time to adjust to river conditions and distribute in the river channel. Release at this location also reduced the losses of tagged Chinook salmon and steelhead to upstream predation and minimized the number of fish that could have exited the system through alternative migration pathways provided by Sutter and Steamboat sloughs.

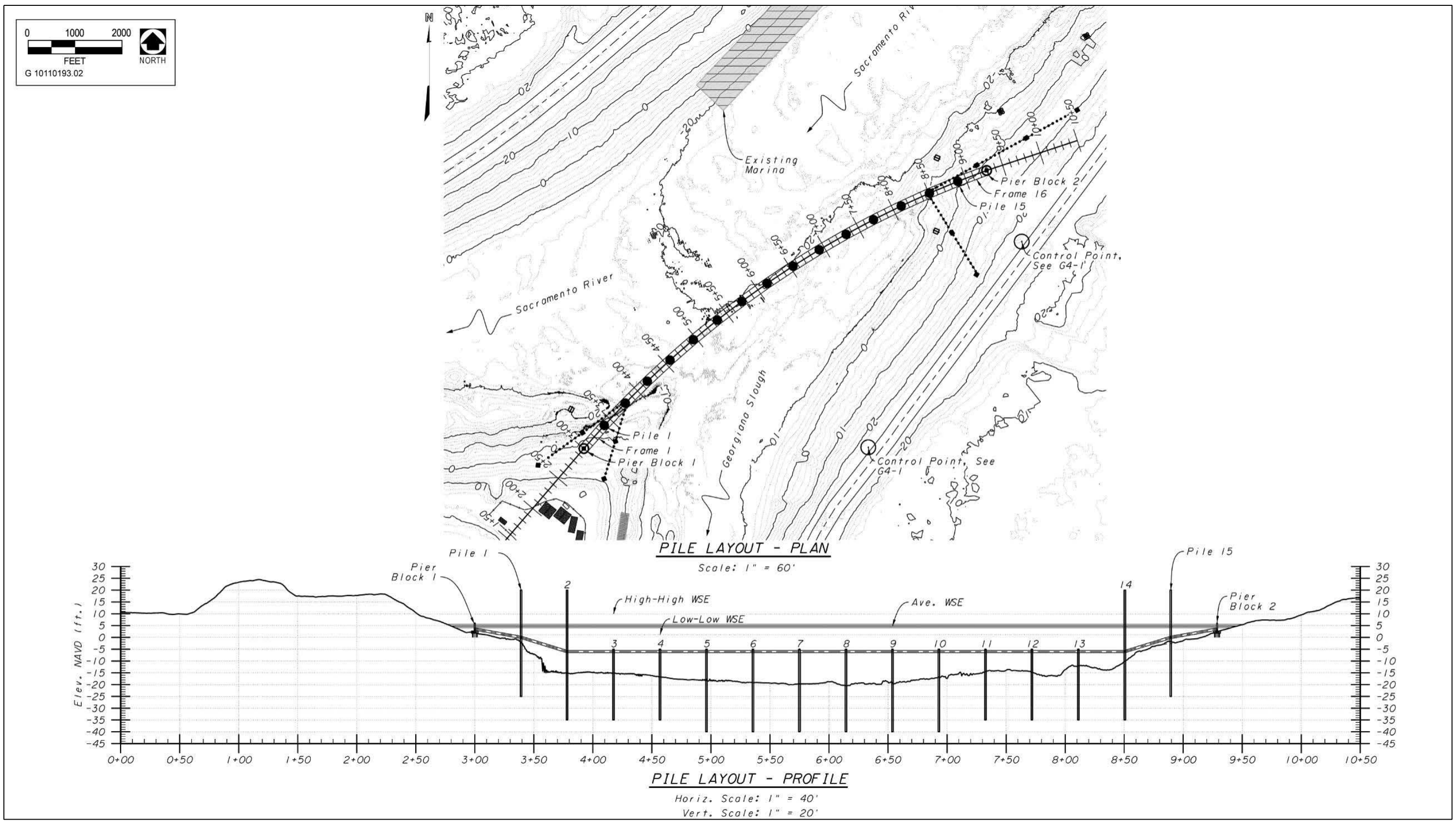
Flow velocity and day/night conditions were monitored continuously immediately upstream from the BAFF location to document the range of conditions likely to affect the movement and fate of tagged Chinook salmon and steelhead released in the study area.

It should be noted that because of the relatively low numbers of steelhead available for the 2012 study and the likely associated limited statistical power for hypothesis testing and model development, this species was evaluated only at a preliminary (pilot) level.

2.5 EXPERIMENT IMPLEMENTATION

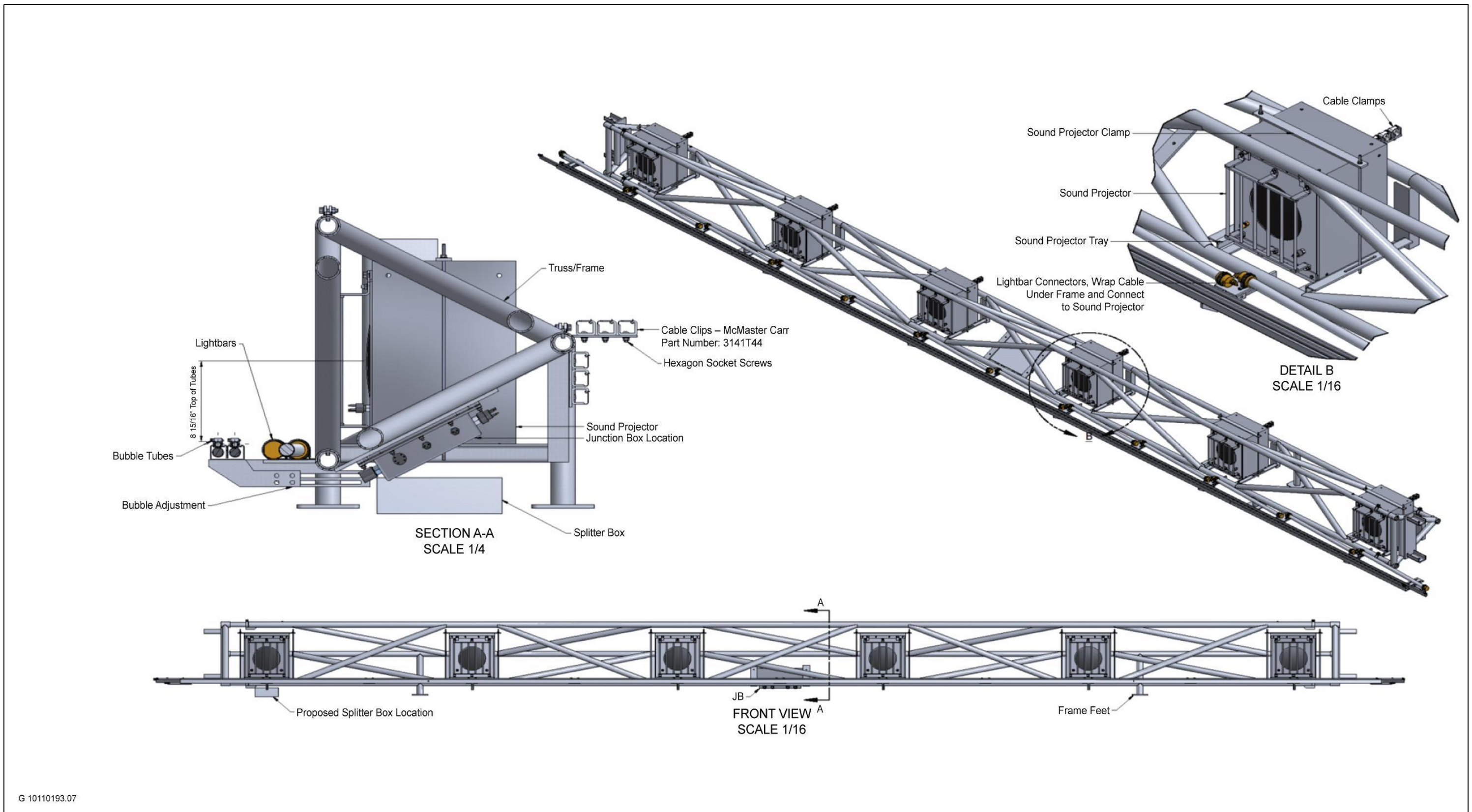
2.5.1 Non-Physical Barrier

Installation of the BAFF began in mid-February 2012. The configuration of the barrier, shown in **Figure 2-2**, is similar to that of the barrier tested in 2011, and its experimental design builds on the results of the 2011 investigations. The barrier includes several fish deterrence technologies, including an air bubble curtain, HIMLs, and sound projectors mounted to a multi-frame steel truss assembly. A single truss-frame is shown in **Figure 2-3**. Diesel generators supplied the power necessary to operate the barrier and associated components. A secure storage container housed the control units, signal generators, and amplifiers. A trailer containing working quarters for the staff conducting 24-hour monitoring was also located at the site.



Source: Data provided by California Department of Water Resources and adapted by AECOM in 2012

Figure 2-2 **2012 BAFF Layout Plan and Profile**



Source: Data provided by Fish Guidance Systems and adapted by AECOM in 2012

Figure 2-3 **Components of the 2012 BAFF System Installed at Georgiana Slough**

DESCRIPTION OF NON-PHYSICAL BARRIER

The BAFF is a patented fish behavioral barrier comprised of an air-bubble curtain into which sound is introduced by means of acoustic transducers fitted at intervals along the base of the bubble curtain (Welton et al. 2002). As a result of the differential velocities of sound in water and air, the sound becomes trapped in the air-water mixture, creating high sound levels concentrated in the bubble curtain, effectively a “wall of sound.” Fish approaching the BAFF encounter exponentially increasing sound levels toward the face of the bubble curtain. Under near-static water conditions, the decay of sound with distance in the water upstream and downstream from the BAFF is rapid, typically falling to a few percent of its peak level within 2-3 m. In faster flowing conditions, turbulence causes sound to disperse more freely, and fish may detect it further from the BAFF. In the most extreme condition, when the bubble curtain is significantly impacted by turbulent river flows, the sound would follow a more uniform rate of decay with distance.

The type of BAFF deployed at Georgiana Slough used electromechanical transducers known as sound projectors and an additional patented development known as SILAS (Synchronized Intense Light and Sound) technology, which synchronizes intense flashing light and sound to provide a combined stimulus to maximize fish guidance. The system used customized sound signals, an air bubble curtain, and directional (focused onto the bubble curtain) HIMLs.

Acoustic Stimulus

Fish Guidance Systems (FGS) investigated the sensitivity of different fish species and found that the most effective acoustic deterrents for multiple species applications fall within the sound frequency range of 5–600 Hertz.

Juvenile Chinook salmon are most sensitive to sound in the range of frequencies between 100 and 300 Hertz (Halvorsen et al. 2009; Oxman et al. 2007). This frequency range, 100-300 Hertz, falls within the range emitted by the sound projectors on the BAFF sound projectors. For the Georgiana Slough installation, FGS MkIII 30-600 Hertz sound projectors were used. Power to the sound projectors was provided by FGS Model 3000 power supply units, and the acoustic signal was controlled by the SILAS system control unit, which operated custom software that controlled and monitored the output of the sound projectors.

The SILAS system control unit and power supply units were connected to the sound projectors with cables that connected to the underwater power and communications hubs, one of which was located on each deployment frame.

The sound projectors were designed and operated to deliver the following source levels:

- Unweighted (peak to peak) at 25 volts 146-159 decibels (dB) re 1 micropascal (μPa), mean152 dB re 1 μPa; and
- Juvenile salmon (peak to peak) at 25 volts 40-53 dB hearing threshold (dBht) re 1 μPa, mean 49 dBht re 1 μPa.

Assuming a standard sound decay rate (inverse square law) and fish sensitivity to sound that is the same as measured by Oxman et al. (2007), the BAFF was designed and operated to create sound field that would result in a fish reaction approximately 80 m outward from the BAFF.

Bubble Curtain

The primary function of the bubble curtain was to contain the sound generated by the sound projectors and to reflect the light projected by the HIMLs (see the following subsection). The sound was encapsulated in the bubble curtain using a unique principle patented by FGS that allows a more precise linear wall of sound to be developed. The bubble curtain was generated by passing compressed air (about 0.2 bar pressure) into a paired series of perforated rubber pipes running along the front of the barrier. The alignment of the bubble curtain determined the guidance line of fish, enabling the barrier to direct them toward the Sacramento River. The trapping of the sound signal in the air curtain prevented saturation of the study area with sound.

Each of the paired series of perforated pipes was supplied with compressed air from opposite ends of a frame section to maintain consistent bubble density along the length of a frame. Output pressures for the feeder pipes were controlled by valves that allowed the pressure across discreet sections to be fine-tuned to achieve consistent bubble curtain density along the length of the BAFF while accounting for the different lengths of pipes and water depths. This fine tuning was important because bubble density affects some fishes' response to air bubble barriers (Patrick et al. 1985).

The steel truss supporting the BAFF was 192 m long, but at high tide, the upstream and downstream ends of the BAFF did not extend to the edges of the river margin. To minimize a functional gap in the BAFF at the extreme margins of the river, a single pipe was extended from the end of the steel BAFF supporting truss to create a bubble curtain up to the shoreline. This pipe was operated in the same way as the pipe that was integrated into the main structure of the BAFF, and each was supplied by dedicated supply pipes. At high tide, when the BAFF was on, these ancillary pipes produced a bubble curtain from the end of the BAFF up to the extreme edge of the river margin. However, no sound projectors or HIML was associated with these two ancillary pipes because if they were exposed during lower water stages, the sound projector and HIMLs could fail because of overheating.

High Intensity Modulated Lights

FGS linear HIML arrays were used to generate the visual stimulus. The HIMLs used in the BAFF were light-emitting, diode-powered devices that created a 180-degree beam of white light that rapidly flashed on and off onto the rising bubble curtain. The bubble curtain served to reflect the beam, making the light more visible to approaching fish. The light signal was controlled by the SILAS system control unit, with two HIML bars connected to each FGS MkIII 30-600 sound projector. The light was generated by the HIML bars, which have a minimum output of 847.44 lux (lux is a unit of illumination) at 1 m. A total of 192 HIML bars, each 1 m long, were used across the length of the BAFF.

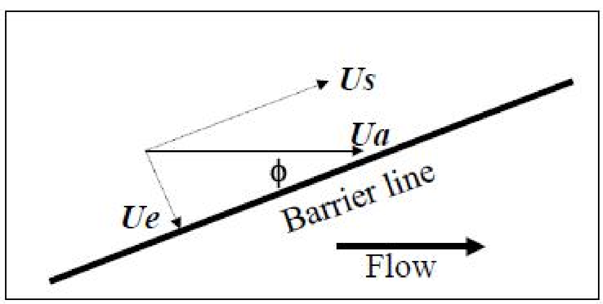
Civil Infrastructure

The BAFF was a 192-m-long steel truss composed of 16 frames, each 12 m long. Each frame had six FGS MkIII 30-600 sound projectors spaced 2 m apart, 12 HIML bars running along the length of the frame, a single FGS underwater power and communication hub, and two lengths of perforated pipe to produce the bubble curtain (**Figure 2-3**). The pipe was positioned along each frame below and upstream from the sound projectors. A mounting plate was attached to the support tray to house the accumulators. The junction of each frame section could be pivoted with the adjacent section, and where needed each frame section was supported at either end with a piling or support column to a pier block. The frame sections could be adjusted vertically at the pile attachments to accommodate the uneven riverbed contour. The sections were positioned along the BAFF line so that as much of the BAFF as possible would be at a depth of less than 3.6 m during high tide. In the main portion of the channel, this location was about 3.6 m from the channel bottom. The top of the frame sections was designed to be at least 2.4 m from the average low-tide water surface elevation. Formed, streamlined concrete pier blocks were used closer to the shore in shallower water to ensure that the system remained in alignment.

Barrier Alignment

The BAFF was aligned so that it had a relatively shallow angle relative to the flow orientation which allowed fish to be deterred while minimizing the effects of the river's hydrodynamic forces. Citing the results of the barrier study at HOR in 2010, which involved a relatively steep barrier angle and higher flows, Bowen and Bark (2012) suggested that such influences can reduce deterrence efficiency. The barrier at Georgiana Slough was positioned with the aim of deflecting fish traveling down the Sacramento River away from the entrance to Georgiana Slough, thus allowing them to continue their migration down the Sacramento River. The downstream end of the BAFF was placed just downstream of the junction of the Sacramento River and Georgiana Slough.

The alignment, and in particular the angle to flow of the river, was a critical element of barrier design. The general principle of angled barrier design as is used, for example, in louver screen arrangements, is that when flow meets the barrier at a small acute angle, fish need to make only a relatively small turn to be guided along the face of the barrier. This alignment also ensures that fish swimming at a relatively low sustained speed can avoid passing through the barrier (Rainey 1985; Turnpenny and O'Keeffe 2005). The swimming direction requiring the lowest escape velocity is at 90 degrees to the line of the barrier. Therefore, the design should ensure that this velocity component is kept below the maximum sustainable swimming speed of the fish over the range of river flows for which the barrier is designed. **Figure 2-4** shows the relevant velocity components for an angled fish barrier.



Note: *Ua* is the channel velocity, *Ue* is the fish escape velocity, and *Us* is the sweeping velocity component along the face of the barrier (Turnpenny and O'Keeffe 2005).

Figure 2-4 **Flow Velocity Components in Front of an Angled Fish Barrier**

The main channel velocity is denoted *Ua*. The velocity perpendicular to the barrier face is the fish's escape velocity, *Ue*. For a barrier angle φ, escape velocity is calculated as:

$$Ue = Ua \sin \varphi$$

The sweeping velocity, *Us*, is the component parallel to the barrier face. It is 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:

$$Us = Ua \cos \varphi$$

The swimming ability of juvenile Chinook salmon was determined by Swanson et al. (2004). They reported a sustained swimming speed of 3.4 body lengths per second (BL/s). The minimum length of Chinook salmon used in the design calculation was 60 millimeters (mm) (based on the selection of a conservatively small size relative to the size of Chinook salmon in the north Delta during outmigration), and the maximum design river velocity was 0.5 meter per second (m/s) (based on design parameters for a BAFF). **Table 2-1** shows the derivation of the barrier angle for these design parameters, which resulted in a barrier angle to flow of 24 degrees. Based on the design assumptions, the maximum approach velocity perpendicular to the barrier was calculated to be 0.204 m/s (within the design discharge range). It should be noted that use of sustained swimming speed values in this calculation provides a margin of safety because fish are capable of significantly higher prolonged and burst speeds for short periods (Beamish 1978). The margin of safety was built into the maximum design approach velocity perpendicular to the barrier, so for a threshold, a slightly higher value was chosen, 0.25 m/s, to categorize low and high velocities. For the samples of deterrence, protection, and overall efficiency, the definition of "high" velocities used was greater than or equal to 0.25 m/s, and "low" velocities were less than 0.25 m/s (see Section 3.2 for additional information).

Table 2-1
Design Angle Parameters for a Barrier Capable of Deflecting Juvenile Chinook Salmon

Attribute		Value
Minimum size of fish		60 mm
Sustained swimming speed		3.4 BL/s
Swimming speed (prolonged)		0.204 m/s
Maximum design channel velocity		0.5 m/s
Required barrier angle		24 degrees
	Angle and Velocity	
Escape velocity	24 degrees	0.203 m/s
Sweeping velocity	24 degrees	0.457 m/s

Notes: BL/s = body lengths per second; mm = millimeters; m/s = meters per second.

2.5.2 ACOUSTIC TAG SYSTEM OVERVIEW

Fish movements were monitored with an acoustic tracking system. The project incorporated Hydroacoustic Technology, Inc.'s (HTI) Acoustic Tag Tracking System (ATS), which uses a fixed array of underwater hydrophones to track movements of fish implanted with acoustic tags. As fish approach the array, the signal transmitted from each tag is detected and the arrival time recorded at several hydrophones. The differences in tag signal arrival times at each hydrophone are used to calculate two-dimensional (2D) and three-dimensional (3D) positions. The ATS includes the following hardware and software components:

- a tag programmer that activates and programs the tag;
- acoustic tags that transmit a pulse of sound at regular intervals;
- hydrophones that function like underwater microphones, capturing sound in a defined volume of water;
- cables connecting the hydrophones to the tag receivers; and
- tag receivers connected to a computer that receives the tag signals from the hydrophones, conditions the signal, and, using specialized software, outputs the data in a format that can be stored in data files.

A complete discussion of the acoustic tag system is provided in **Appendix A.**

SYSTEM COMPONENTS

Acoustic Tags

All tags used in this study operated at a frequency of 307 kilohertz (kHz) and were encapsulated with a nonreactive, inert, low-toxicity resin compound. The tags used "pulse-rate encoding," which provided an increased detection range, an improved signal-to-noise ratio and pulse-arrival resolution, and decreased position variability when compared to other types of acoustic tags (Ehrenberg and Steig 2003). Pulse-rate encoding uses the interval between each transmission to detect and identify the tag. Each tag was programmed with a unique pulse rate to track movements of individual tagged fish.

The pulse rate is measured from the leading edge of one pulse to the leading edge of the next pulse in sequence. Because the tags had slightly different pulse rates, they could be individually identified. The timing of the start of each transmission was precisely controlled by a microprocessor in the tag. Test tag frequency periods ranged between 2.003 and 3.474 seconds. The amount of time that the tag actively transmits is the pulse length (or pulse duration). For this study, the transmit pulse length was 3.0 milliseconds.

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. When this tag coding option is used, each tag is programmed with a defined primary tag period, and also with a defined secondary transmit signal, called the subcode. This subcode defines the precise elapsed period between the primary and secondary tag transmit signals. Thirty-one different subcodes are possible for each tag period, which resulted in more than 100,000 total unique tag ID codes being available for use in the 2012 GSNPB Study.

Hydrophones

HTI Model 590 hydrophones were installed for this study, and several more were used for pre-release tag testing operations. Model 590 hydrophones operate at 307 kHz and include a low-noise pre-amplifier. Hydrophone directional coverage was about 330 degrees, with equivalent sensitivity in all directions except for a 30-degree limited sensitivity cone directly behind the hydrophone where the cable was attached. The hydrophone sensor element tip was encapsulated in specially treated rubber to ensure long-term reliability with acoustic impedance close to that of water. The hydrophone and connector housing were made of a corrosion-resistant aluminum-bronze alloy. Cables were twisted pair wire and double shielded for noise reduction.

The hydrophone pre-amplifier circuit provided signal conditioning and background noise filtering for transmission over long cable lengths and in acoustically noisy environments. A calibration circuit in the pre-amplifier provided a method for field testing hydrophone operation and was used to measure the signal time delays between hydrophones in the array. The Model 590 hydrophones included temperature sensors to measure water temperature variations and their effect on the velocity of the signal in water.

To measure signal time delays, the calibration circuit for each hydrophone was rotationally set to transmit ("ping"), whereas all other hydrophones were set to receive. This procedure was repeated for all hydrophones in the array. Data from each hydrophone were processed to measure the time delay and water temperature. Accurate measurement of signal time delays between hydrophones provided the position data to locate the array in the Universal Transverse Mercator coordinate system (UTM) or latitude/longitude coordinates (Lat/Long) and provided the resolution necessary for submeter 3D positioning.

Acoustic Tag Receiver

Two HTI Model 290 Acoustic Tag Receivers (ATRs) were used to receive hydrophone data at the BAFF. The ATR is designed to receive up to 16 separate channels; one channel is assigned to each hydrophone. Each ATR was connected to a personal computer used to analyze and store the acoustic data. The two ATRs were synchronized using an internal global positioning system (GPS) in each of the receivers. An individual raw data file was created for each sample hour. Filters in the ATR were set to identify the acoustic tag sound pulse and discriminate tags from the ambient background noise.

When the tag signal was received by the ATR, a series of signal processing steps were completed. The envelope detector received the signal and output the positive "envelope" with the carrier frequency removed. This detected echo envelope was then digitized at a rate of 12 kHz. A real-time adaptive noise threshold was set based on a 1-second window of the background noise level for each hydrophone independently, which was updated every 0.083 millisecond. The pulse length (or duration) of each pulse that exceeds a predetermined threshold was measured at the -3-, -6-, and -12-dB points, and the pulse peak amplitude was located and measured.

The ATR pulse measurements were reported for each single echo from each hydrophone and written to Raw Acoustic Tag (*.RAT) files using the AcousticTag program. Each *.RAT file contained header information for data acquisition settings followed by the raw echo data. Each raw echo data file contained all acoustic signals detected during the period, including signals from tagged fish and additional unfiltered acoustic noise.

Software—MarkTags and AcousticTag

Two separate programs were used to process acoustic tag data: AcousticTag and MarkTags. AcousticTag was used initially to acquire data from the ATR and store it in raw acoustic echo files. MarkTags read the raw acoustic echo files, identified tag signals, and created acoustic tag files. These acoustic tag files were used again in AcousticTag to position the tags in 3D space.

AcousticTag acquires data and stores it in *.RAT files. It is important to note that 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 in these files are not tag data but are derived from secondary sources (e.g., ambient noise, multipath). Thus, the first important phase of data processing is to select the acoustic echoes that have been received directly from tags and assign unique tag IDs to these echoes.

The echo selection process is 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 plot shows the detected arrivals in the time window equal to the pulse-rate encoding of a particular tag (Ehrenberg and Steig 2003). The results of the tag selection process completed in MarkTags is written to Tracked Acoustic Tag (*.TAT) files. These files contain the individual raw acoustic echoes that have been assigned a tag ID but no spatial positioning. AcousticTag performs the triangulation calculations and provides a database of point locations for each fish.

Tag Programmer

Each of the acoustic transmitters needs to be activated and programmed with unique properties (e.g., tag code) prior to being implanted in a study fish. The TagProgrammer application was used to set the individual settings when programming a tag.

Hydrophone Placement Geometry and Position Calculation

The principle used to determine acoustic tag positions is the same principle used to determine positions using a GPS. The acoustic tag transmits a signal that is received by at least four hydrophones. Because the positions of the four hydrophones are known and the relative signal arrival times at the hydrophones can be measured, the locations of the tagged fish can be estimated. In particular, if h_{ix}, h_{iy}, h_{iz} specify the x,y,z location of the i^{th} hydrophone and F_x, F_y, F_z specify the unknown x,y,z locations of the tagged fish, then the travel time from the tagged fish to the i^{th} hydrophone, t_i, is given by:

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

where: c is the velocity of sound.

Unfortunately, the absolute travel time cannot be directly measured. However, the differences between the arrival times of the signal at the various hydrophones ($t_i - t_j$) can be measured as given by:

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

With four hydrophones, there are three distinct signal-arrival time-difference equations. The system of nonlinear equations is determined by solving the tagged fish coordinates, F_x, F_y, F_z, such that the mean squared difference between the measured (left side of the previous equation) and calculated (right side of the previous equation) time differences are minimized. Additional information on the acoustic tag system is presented in **Appendix A**, “2012 GSNPB Acoustic Tag System Data Collection Plan.”

MONITORING EQUIPMENT DEPLOYMENT AND HYDROPHONE ARRAY DESIGN

Monitoring equipment was deployed starting in February 2012, and the 34-node array was completed on March 5, 2012. Deployment activities began with installation of hydrophones and all other in-water components. Model 590 hydrophones were installed on bottom or surface mounts designed for the environmental and flow conditions at each location. The different configurations used for bottom- and surface-mounting configurations are discussed in the next section. Cables attached to the hydrophones ranged in length from 15 m to 150 m. Hydrophone cables were paired with tensioned aircraft cable to increase cable stiffness and strength.

Multiple hydrophones were installed in the Sacramento River immediately upstream, downstream, and adjacent to the BAFF to monitor tagged fish as they encountered and responded to the barrier. These hydrophones were referred to as the study array. Additional hydrophones, referred to as the peripheral hydrophones, were installed to detect tagged fish outside of the area of the BAFF. Each of the peripheral hydrophones was combined with autonomous data loggers and operated independently using air card modems for communication access and remote data downloading.

The array hydrophones, peripheral hydrophones, and cable assemblies were deployed and tested before field implementation of the 2012 GSNPB Study. All equipment was bench-tested and calibrated before installation. Hydrophones were installed and cables were routed to electronic equipment housed in secure, climate-controlled structures supplied with 110-volt AC power located on shore.

Hydrophones were positioned as part of barrier deployment and monitored on-site for use in documenting the response of tagged salmon, steelhead, and tagged predatory fish to the BAFF when it was either on or off. This monitoring system allowed on-site, real-time detection and monitoring of movement by tagged fish into and through the study area. The system was maintained throughout the study period.

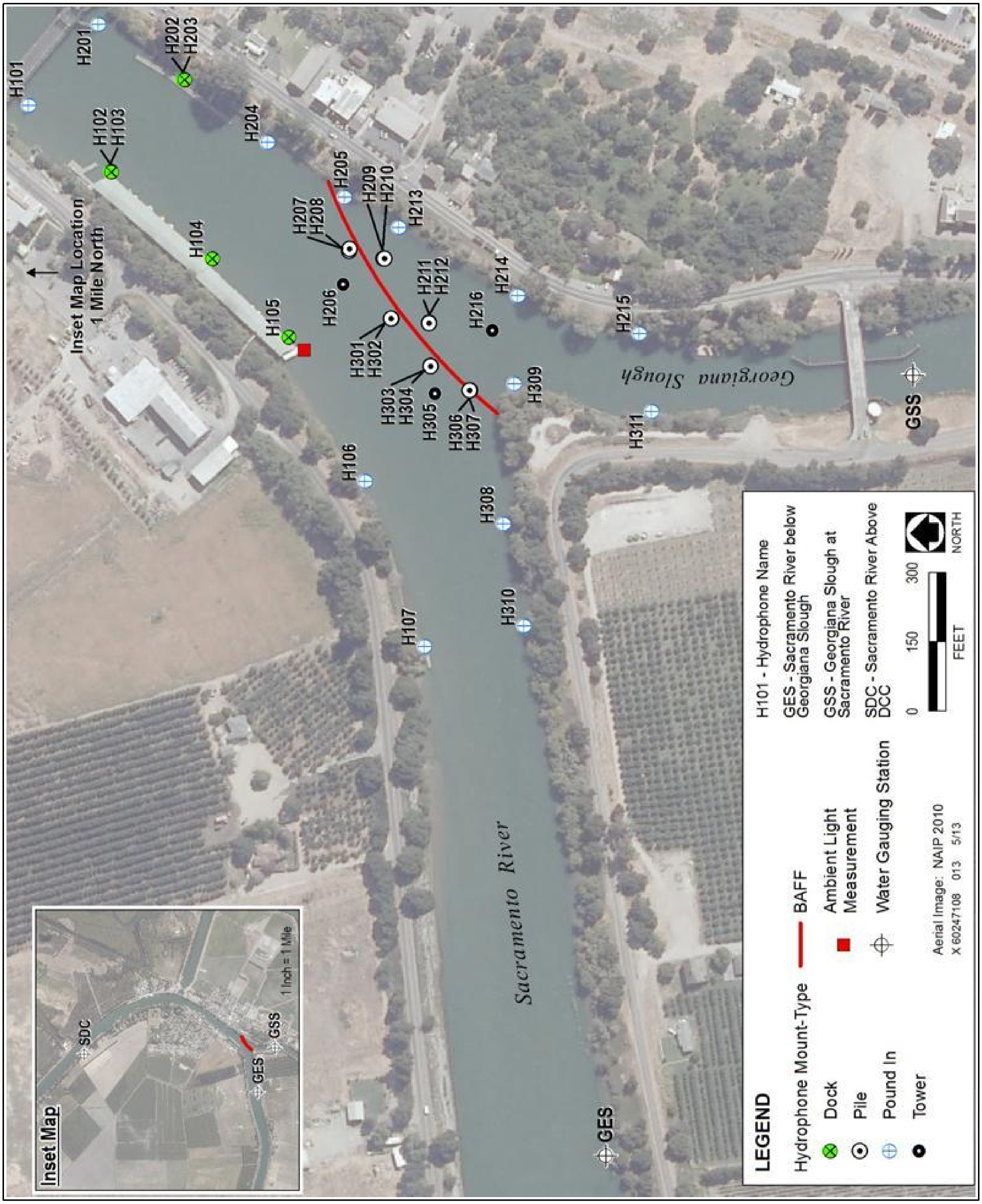
Hydrophone Array at the Non-Physical Barrier

The hydrophone array was installed near the BAFF. Hydrophones were positioned on both the Sacramento River side and the Georgiana Slough side of the BAFF. They were placed so that high-quality 2D and 3D tracks could be obtained throughout these study reaches.

Hydrophones were deployed in the array using several types of mounting hardware. The precise location of hydrophones in the array was measured on site using a GPS unit and the procedure for calculating hydrophone placement geometry and positioning known as the “ping-around.” The effective range of detection and overlap of hydrophones in the array was also examined on site by actively moving a transmitting tag throughout the array and verifying consistent detection and positioning of the tag (termed the “tag drag” procedure).

An automated data downloading and storage system for the hydrophone array was set up, operated, and maintained during the duration of the study.

Hydrophone array locations are presented on **Figure 2-5**.



Source: Data provided by HTI, USGS, and DWR and adapted by AECOM in 2012

Figure 2-5 **Hydrophone Array and Other Data Collection Instrument Locations**

Bottom-Mounted Hydrophones

Several hydrophones in the study array and peripheral sites were deployed on the river bottom. The type of bottom mount used was dependent on flow velocities and the position of the hydrophone relative to the shore. Two types of bottom mounts were used.

Tower Mount Bottom-Mount Configuration

Tower mounts are large, heavy river mounts used to minimize hydrophone movement after positioning (**Figure 2-6**). These types of mounts were used in offshore areas or other areas of high flow.

Near-Shore ("Pound-In") Bottom-Mount Configuration

Pound-in mounts were mounts with large stakes used to mount hydrophones near shore (**Figure 2-7**).

Bottom-Mount Deployment Methods

Hydrophones were attached to bracket plates bolted to the mount frame. Cables were attached to the hydrophones and secured to the mount frame with cable ties. Offshore tower mounts were deployed from a boat using a winch (**Figure 2-6**). Near-shore pound-in mounts were also deployed from a boat.

Surface-Mounted Hydrophones

Surface-mounted hydrophones were attached to existing underwater structures such as docks and pilings. Dock mounts were used and attached to underwater structures where available (**Figure 2-8**). Floating pile mounts were also used at selected piles to allow for varying surface positions associated with changes in water stage elevation (**Figure 2-9**).

Peripheral Hydrophones

Peripheral hydrophones were attached to self-contained receivers that could be accessed remotely using cell modems and an Internet-based file upload and storage system. Receivers for the peripheral hydrophones were housed in secure structures supplied with 12-volt DC power from deep-cycle batteries. Batteries were charged with solar panels or 120-volt AC battery chargers where available. **Figure 2-1** shows the locations of the peripheral hydrophone sites.

An automated data downloading and storage system for the peripheral hydrophone sites was set up, operated, and maintained during the duration of the study.

Source: HTI

Figure 2-6 **Representative Photograph of a Tower Mount**

Source: HTI

Figure 2-7 **Representative Photograph of a "Pound-In" Mount**

Source: HTI

Figure 2-8 **Representative Photograph of a "Dock" Mount**

Source: USGS

Figure 2-9 **Representative Photograph of a Floating Pile Mount**

2.5.3 FISH AND FISH TAGGING

The 2012 GSNPB Study used juvenile late fall-run Chinook salmon and juvenile steelhead reared at the U.S. Fish and Wildlife Service's (USFWS) Coleman National Fish Hatchery. Ration level and holding conditions in the hatchery before tagging were managed, to the extent possible, to produce Chinook salmon ranging in size from 110 to 140 mm fork length (FL) and juvenile steelhead ranging from 150 to 200 mm FL. Late fall-run Chinook salmon, the primary species of interest for the study, had a size range greater than that of the fall-run, winter-run, and spring-run Chinook salmon that migrate past the mouth of Georgiana Slough in spring (Vogel and Marine 1991). Study fish were held at the hatchery compound throughout the study period, and small groups of fish were transported to the tagging location daily to meet tagging requirements.

TAGGING LOCATION

Fish holding, tagging, and release operations were conducted on a houseboat moored at the junction of the Sacramento River and Steamboat Slough, about 8.9 km upriver of the BAFF. The location and configuration of the tagging operation were selected to: 1) allow fish to be held in Sacramento River water both before and after tagging; 2) facilitate the delivery of untagged fish from Coleman National Fish Hatchery; and 3) facilitate the release of tagged fish with minimal handling. The houseboat and the supporting dock structure to which it was moored met these objectives and provided an effective work platform (**Figure 2-10**).

EXPERIMENTAL DESIGN OF FISH RELEASES

A variety of factors may affect the behavior of juvenile Chinook salmon and steelhead released into the Sacramento River upstream from Georgiana Slough. Among these factors are river flows and tidal hydrodynamics that vary daily in response to ebb and flood tidal conditions and the magnitude of Sacramento River flows. The migratory behavior of juvenile Chinook salmon and steelhead may also vary throughout the day/night cycle. To address several of these factors, tagged Chinook salmon and steelhead were released at regular intervals throughout the day/night cycle and the study period. Small subgroups of about four to seven tagged fish were released every 3 hours on each study release date, resulting in eight subgroups daily (midnight, 3 a.m., 6 a.m., 9 a.m., noon, 3 p.m., 6 p.m., and 9 p.m.). The continuous release of tagged fish at 3-hour intervals allowed study fish to be exposed to day and night conditions and flood and ebb tidal conditions under a variety of Sacramento River discharges throughout the study period.

TAGGING SCHEDULE

Releases of tagged Chinook salmon began on March 6, after the BAFF and monitoring equipment had been installed and tested. On March 7, fish releases were interrupted because the BAFF was shut down for inspection and to make adjustments. Following barrier adjustments and inspection, fish releases recommenced on March 11 and continued daily until April 23 (see **Appendix B**). Steelhead tagging operations occurred during two short periods during the Chinook salmon study period. Releases of tagged steelhead for the first session began on March 18 and ended on March 20. The second steelhead period began on April 11 and continued until April 15 (see **Appendix B**).

For both Chinook salmon and steelhead, the daily tagging schedule was designed to minimize the variability in both before tagging (hereafter referred to as pretag) and after tagging (hereafter referred to as posttag) holding times for the eight subgroups of study fish released within a 24-hour period. The pretag and posttag holding times were defined by the standard operating procedure (SOP) used for fish handling and tagging (**Appendix C**). Two tagging sessions (four subgroups per session) were used each day to minimize variability in holding times. A morning session (between 8–10 a.m.) was used to tag the 9 a.m., noon, 3 p.m., and 6 p.m. release groups, and an afternoon session (between 2–4 p.m.) was used to tag the 9 p.m., midnight, 3 a.m., and 6 a.m. release groups. On dates when both Chinook salmon and steelhead were tagged, tag session times were adjusted somewhat to allow time to tag additional fish, while maintaining the limits defined in the SOP (**Appendix C**, “2012 GSNPB Summary of Standard Operating Procedures”).

TRANSPORT TO TAGGING LOCATION AND PRETAG HOLDING

Groups of Chinook salmon were transported daily from Coleman National Fish Hatchery to the tagging location. Juvenile steelhead were transported daily during the two steelhead tagging sessions. The transport system consisted of three 75-liter perforated containers held in an insulated tank, mounted on the bed of a truck. Oxygen cylinders, regulators, and diffusers provided aeration to the tank during transport.

Transport operations began at about 7 a.m. at the hatchery in an effort to complete the 3- to 4-hour transport to the tagging location with minimal risk of increased water temperatures. The insulated tank was filled with water from the hatchery (mean temperature of 10.7 degrees Celsius [°C]), and non-iodized salt was added to achieve a working concentration of 5–7 parts per thousand to reduce osmotic stress. Oxygen was supplied to the tank through diffusers to maintain dissolved oxygen concentration near saturation throughout the transport. Fish were loaded into the three 75-liter containers at a conservative loading density, based on accepted hatchery transport guidelines for the transport of hatchery-produced juvenile salmonids. Chinook salmon and juvenile steelhead were transported separately, using a full duplicate transport system, on dates when both species were transported, to reduce handling stress (Liedtke et al. 2012).

Approximately 38–40 Chinook salmon were transported daily, distributed approximately equally across the three transport containers. On steelhead transport dates, about 55-57 steelhead were loaded equally across the three containers. The number of fish transported on each date was based on the requirements of the tagging operation for the following day, with additional fish to allow fish selection based on condition and/or size.

Rations were withheld from fish on the day before transport to reduce stress during transport, handling, and subsequent surgical implantation procedures (Liedtke and Wargo-Rub 2012:55). To allow the bulk of the study fish to maintain a normal feeding regime, groups of fish to be transported were isolated in a small holding tank about 24 hours before transport.

Water temperature, salinity, and dissolved oxygen concentrations in the transport tank were monitored at the hatchery, during the transport, and upon arrival at the tagging location.

Upon arrival at the tagging location, the 75-liter containers were removed from the transport tank and placed in non-perforated 75-liter containers to prevent water loss. The containers were carried from the transport truck to the dock adjacent to the houseboat. Water temperatures in the containers were measured and compared to the water temperature of the Sacramento River at the tagging location. If the difference in water temperature between the containers and the Sacramento River was more than 2°C, river water was added to the containers to adjust the water temperature at a rate of about 5°C per hour until the water temperature differential was within 2°C. After the water temperature in the containers was within 2°C of the river temperature, the perforated containers were gently immersed in the river and secured in polyvinyl chloride (PVC) pipe floating frames. The frames were tethered to the dock so that Sacramento River water flowed through each container (**Figure 2-10**).

Source: Photograph taken by AECOM in 2012

Figure 2-10 Representative Photograph of Fish-Holding Containers Tethered to Dock System

Fish were held for 18-24 hours before tagging to allow them to adjust to Sacramento River conditions and recover from handling and transport stress. Water temperature and dissolved oxygen concentration adjacent to fish-holding containers were monitored regularly. The SOP for fish transportation is presented in **Appendix C**, "2012 GSNPB Summary of Standard Operating Procedures."

There were a total of 55 separate fish transport events during the study period. The mean change in water temperature in the transport tank that occurred between the hatchery and the tagging location was <0.5°C. The mean difference in water temperature between the transport tank and the Sacramento River at the tagging location was 2.3°C, and 42 of the 55 transport events (76.4 percent) required some tempering to adjust water temperatures.

ACOUSTIC TAGS

Juvenile Chinook salmon were surgically implanted with HTI Model 795Lm microacoustic tags (see also Section 2.5.2). The tags have a typical battery life of about 15 days and a dry weight of 0.65 gram, and they transmit a unique acoustic signal at a rate of one pulse every 2-4 seconds. Chinook salmon were selected for tagging if they weighed at least 13 grams so that the anticipated tag burden (defined as transmitter weight in air relative to fish weight in air) would be less than 5 percent, following published recommendations (Adams et al. 1998; Martinelli et al. 1998; Liedtke et al. 2012). The mean tag burden for juvenile Chinook salmon used in the study was 2.2 percent (range: 0.6 to 5 percent).

Juvenile steelhead were surgically implanted with HTI Model 795 LD microacoustic tags. These tags were larger than the transmitters used in Chinook salmon (1.0 gram in air), but they had similar battery life and transmission properties. Steelhead were selected for tagging if they weighed at least 20 grams. The mean tag burden for juvenile steelhead used in the study was 1.0 percent (range: 0.6 to 1.8 percent).

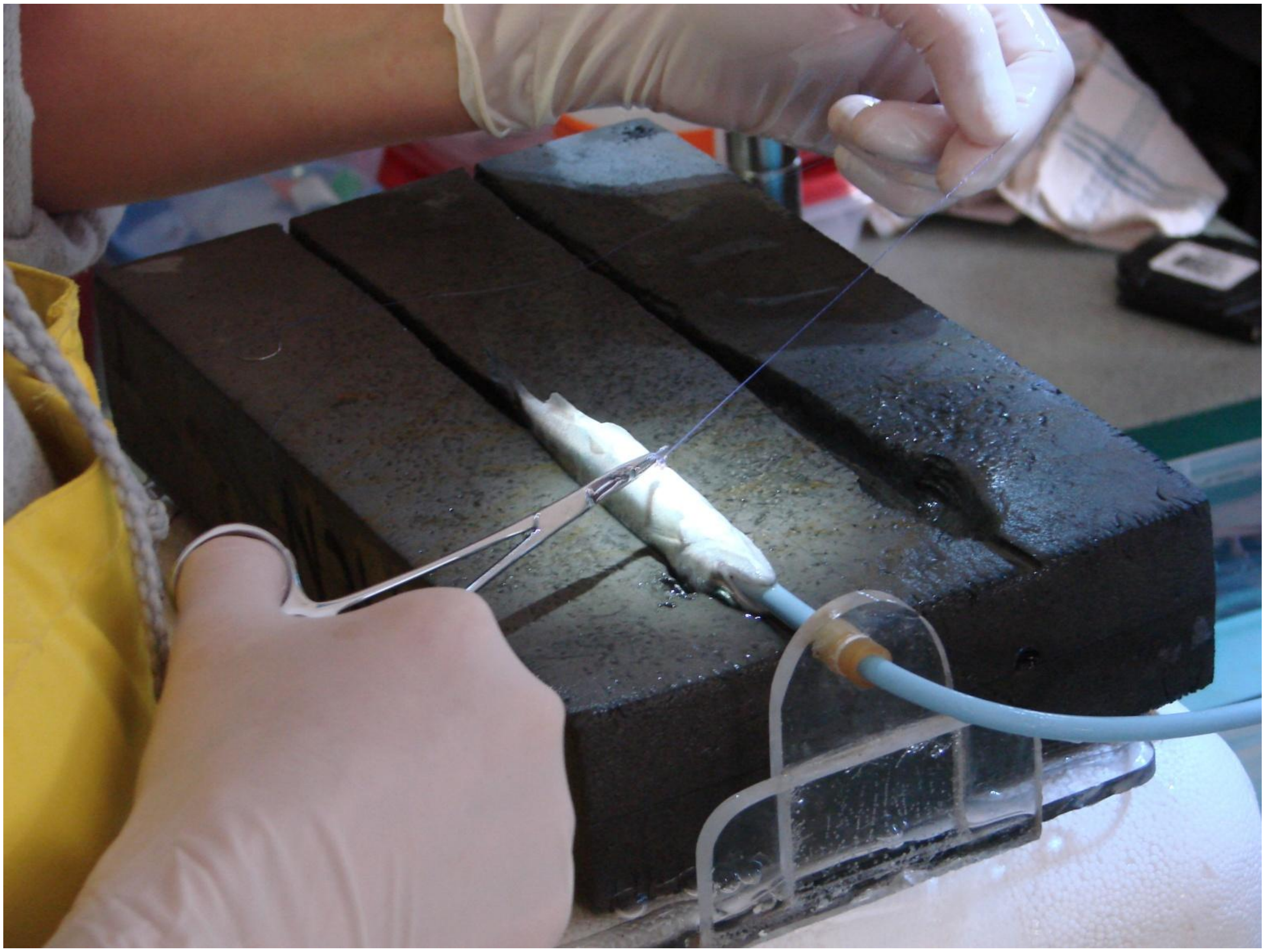
Transmitters were activated and programmed the morning of each tagging operation to maximize usable tag life. Before the transmitters were delivered to the tagging location, each was checked to ensure that it was functioning properly.

SURGICAL IMPLANTATION PROCEDURES

Fish handling, holding, and tagging procedures were based on a well-established SOP developed for juvenile salmon in the Columbia River Basin (Liedtke et al. 2012) and modified to meet the experimental design of this evaluation. To limit the potential influence of individual taggers, two proficient taggers were used throughout the study period, rotating regularly to balance their contribution to the overall number of tagged fish for each species.

Fish were held for 18–24 hours after transport and before tagging to allow them to recover from the stress of transport and handling. Following activation and programming, transmitters were disinfected in chlorhexidine diacetate solution and rinsed with distilled water before implantation. Surgical instruments were sterilized daily and disinfected between individual surgical procedures.

Study fish were anesthetized in 50-70 milligrams per liter tricaine methanesulfonate [MS-222] buffered with sodium bicarbonate to stage 4-5 anesthesia (Liedtke et al. 2012). The time in anesthesia was monitored for each fish and did not exceed 5 minutes. Fish were removed from anesthesia and were weighed (to the nearest 0.1 gram), measured (FL to the nearest mm), and quickly evaluated for general condition. Fish with obvious deformities or significant (>20 percent per side) scale loss were not selected for tagging. A surgical platform (V-shaped foam trough) was used to secure the fish with the ventral surface exposed while the gills were perfused with a maintenance solution of buffered MS-222 via a gravity-feed system (**Figure 2-11**). An incision was made 2-3 mm anterior to the pelvic girdle and 2-3 mm away from and parallel to the midventral line using a microsurgical scalpel. The incision was long enough to allow insertion of the transmitter without tearing the surrounding tissue (i.e., slightly longer than the diameter of the transmitter). The disinfected acoustic transmitter was inserted into the body cavity through the incision, and the incision was closed using two simple interrupted sutures. The suture material was Vicryl+, in 5/0 size for Chinook salmon and 4/0 size for steelhead. Following the surgical procedure, fish were transferred to a recovery container with a high concentration of dissolved oxygen (120–130 percent) to aid recovery from anesthesia. After fish were oriented and responsive to stimuli, they were transferred to 120-liter containers for posttag holding. Mean surgical procedure time was less than 2 minutes, and the mean amount of time fish were exposed to air (from removal from anesthesia until placement in a recovery container) was less than 3 minutes. Full details of fish handling and surgical procedures are provided in the SOP (**Appendix C**, "2012 GSNPB Summary of Standard Operating Procedures").



Source: Photograph taken by AECOM

Figure 2-11 **Surgical Implantation of an Acoustic Tag**

POSTTAG HOLDING AND RECOVERY

After recovering from anesthesia, tagged fish were transferred from the recovery container into a posttag holding and release container (i.e., a 120-liter perforated container). Each 3-hour release group was held in a separate container, tethered to the dock at the tagging location. The containers were supported by floating frames made of PVC pipe so that the upper quarter of the container was above the water. This configuration reduced the risk of fish escaping and provided tagged fish access to the air-water interface so that they could regain neutral buoyancy before being released (Liedtke and Wargo-Rub 2012; Liedtke et al. 2012). After they were placed inside the holding container, the fish were not handled again before release. Fish remained in the release containers for 18-30 hours after tagging.

2.5.4 FISH RELEASES

Tagged fish were released at regular intervals throughout the diel cycle and the study period. Small subgroups of about four to six tagged fish were released every 3 hours on each study release date, resulting in eight subgroups daily (midnight, 3 a.m., 6 a.m., 9 a.m., noon, 3 p.m., 6 p.m., and 9 p.m.).

TAG VERIFICATION

Two approaches were used to confirm that all study transmitters were functioning properly before the tagged fish were released. The first approach involved using a hydrophone positioned near the release containers. The hydrophone and corresponding receiver recorded the acoustic signals from all transmitters in tagged fish held at the tagging location for the 18- to 30-hour posttag holding period. The second approach involved using a separate hydrophone, which was inserted into an individual release container within 30 minutes of the planned release time. This redundant approach to tag verification allowed the detection of non-functioning tags before release.

FISH RELEASES

Immediately before release, the container holding the release subgroup was partially dewatered to visually observe the group of tagged fish. As part of the standard operating procedures, dead or moribund fish would be removed from the release container, and transmitters would be recovered and stored for evaluation and possible reuse. Individual fish with compromised health would also be removed from the container and euthanized.

Release containers were lifted into a boat for transport to the release location. The boat transported tagged fish from the tagging location downriver approximately 0.7 km, past the confluence with Steamboat Slough, to the release location, approximately 8.9 km upriver of the BAFF, in the center of the river channel. Tagged fish were released into the river near the water surface by allowing them to swim out of the release container.

SUMMARY OF TAGGED FISH RELEASED FOR BARRIER EVALUATION

In total, 55 groups of fish were surgically implanted with acoustic transmitters during the study period, consisting of 1,501 juvenile Chinook salmon and 299 juvenile steelhead. Chinook salmon used for the evaluation had a mean FL of 138 mm (range: 104–215 mm) and a mean weight of 29.4 grams (range: 12.9 to 106.8 grams) (**Appendix B**). Juvenile steelhead had a mean FL of 215 mm (range: 119–258) and a mean weight of 101.5 grams (range: 54.3 to 164.5 grams) (**Appendix B**). None of the tagged fish died during the 18- to 30-hour posttag holding period, and no fish were euthanized immediately before release because of compromised health.

TAG RETENTION AND FISH HEALTH STUDIES

To evaluate tag retention, tagger proficiency, and potential transmitter effects on fish performance, groups of tagged fish were held in tanks and evaluated 30 days after tagging. The tank studies were conducted at the California-Nevada Fish Health Laboratory and involved both juvenile Chinook salmon and steelhead. Detailed procedures and findings are presented in **Appendix D**, “2012 GSNPB Fish Tagging Effects Study.”

2.5.5 PREDATOR FISH TAGGING AND MONITORING

A number of predatory fish species are known to reside year-round in the vicinity of the study area, including striped bass, smallmouth bass (*Micropterus dolomieu*), largemouth bass (*Micropterus salmoides*), spotted bass (*Micropterus punctulatus*), and Sacramento pikeminnow (*Ptychocheilus grandis*). Previous field studies have shown evidence of predation on juvenile salmonids in the Delta, including predation at the BAFF in the lower San Joaquin River at HOR (Nobriga and Feyrer 2007; Hanson 2009; Bowen et al. 2012; Bowen and Bark 2012). Target species for the 2012 GSNPB Study were striped bass, smallmouth bass, largemouth bass, spotted bass, and Sacramento pikeminnow. Target species were selected because they are present year-round and are believed to be the primary predatory species in the Sacramento River and Georgiana Slough in the vicinity of the study area. The target tagging sample size was a total of 50 predator fish representing the different species. Current information and data describing predator community structure in the study area were unavailable. Historical sampling data were used to determine tagging proportions among target species such that the tagged sample approximated the natural predator community structure in the study area. Tagging proportions were based on sampling data collected by the California Department of Fish and Wildlife (DFW) (formerly known as the California Department of Fish Game) from 1995 through 1999 in Taylor Slough, Steamboat Slough, the Sacramento River at Threemile Island and at Paintersville, and the San Joaquin River at Bradford Island. Based on these data, the minimum, target, and maximum tagging sample size for each target species was selected (see Section 3.7.3).

Sampling and tagging occurred throughout the study period to account for: 1) the potential of tagging fish that may migrate outside of the project area; and 2) the wide range of environmental conditions study fish encountered. A small group of predators were tagged, released, and monitored before the first release of study salmonids. The pre-project sampling and tagging schedule provided the broad framework for the study duration. However, under an adaptive strategy, the schedule was flexible, and change was based on various factors, including weather conditions, the number of tagged predators in the study area at any one point in time (the ideal number for efficient tracking was determined to be five or fewer), sampling and tagging success, and the amount of time tagged fish stayed within the detection range of the acoustic detection and monitoring network.

PREDATOR CAPTURE METHODS

Sampling was confined to a 1-mile radius from the divergence of Georgiana Slough from the Sacramento River, however, sampling efforts were focused in the immediate study area (delineated by the most upstream and downstream hydrophones depicted in **Figure 2-5**) to avoid transportation and introduction of predators into the hydrophone array. Sampling extended beyond the immediate study area when fish were difficult to catch or when the search led to other areas where predatory fish were concentrated.

Sampling for predatory fish was conducted from a 16-foot aluminum fishing boat equipped with a 60-horsepower outboard engine and from the release dock. Four crew members generally participated on each sample day, with two stationed at a release dock located within the study array and two roving the study area in the fishing boat. The two crew members stationed at the release dock were tasked with receiving and caring for fish, conducting surgeries, providing post-surgery care and release. The roving crew was responsible for capturing predatory fish and transporting them to the release dock. Predatory fish were captured using hook-and-line with dead bait and artificial lures. Circle hooks were used during bait fishing to minimize hooking injuries.

Captured predators that received hooking or other injuries and/or displayed abnormal behavior were not tagged and were immediately released. Hooks were removed carefully following capture and fish were immediately placed in well-aerated livewells filled with river water. The fishing boat livewell consisted of a large cooler outfitted with a recirculating pump and spray bar and was filled with river water using a bilge pump and hose. On each sample day, a minimum of six in-river livewells were attached to the release dock. These livewells were used to hold fish before and after surgery. Similar to the juvenile salmon tagging operation, the in-river livewells consisted of perforated large, plastic storage containers modified with a PVC collar for flotation.

All tagged predatory fish were released at the release dock in the study area just upstream of the BAFF. Total length (mm), weight (grams), species and capture location (GPS) were recorded for all fish captured by the fishing boat crew.

Predatory fish of sufficient size to effectively prey on the tagged juvenile Chinook salmon and steelhead were eligible for tagging. Gape size and not fish length generally dictates the size range of prey. It was at the discretion of crew members to select predators appropriate for tagging, although the minimum tagging length for target species was approximately 300 mm total length for *Micropterus* spp. (smallmouth, largemouth, and spotted bass), and approximately 360 mm total length for striped bass and Sacramento pikeminnow. Crews attempted to capture and tag fish with a range of lengths so that the length range of the tagged sample approximated the length range of the predator assemblage using the study area.

SURGICAL TAG IMPLANTATION METHODS

A mobile surgery station was assembled on each sample day on the release dock. Tags were activated, programmed, and delivered to the surgery station prior to capture efforts each tagging date. Captured predatory fish were transported from the fishing boat livewell into a 5-gallon bucket of water and placed in one of the in-river livewells, which received a continuous supply of water from the Sacramento River.

The surgical environment was maintained in a clean condition throughout all procedures. The surgical station was intermittently cleaned and wiped down with a solution of disinfectant, and surgical instruments were placed in a disinfectant bath (i.e., chlorhexidine diacetate solution) before and after surgical procedures. Surgical instruments were transferred to a freshwater rinse before surgery. All equipment used for capture, holding, anesthesia, surgery, recovery, and movement of fish during the project were thoroughly cleaned and disinfected to minimize the potential for pathogen transfer among fish populations.

Fish were transported from the in-river livewells to the surgery station in 5-gallon buckets containing freshwater and placed in a large surgery station livewell (identical to the fishing boat livewell described above) containing aerated water and diffused carbon dioxide (CO_2). The oxygen level in the surgery station livewell was maintained near saturation via a diffuser, and approximately 7-10 grams of salt was added per liter of water. Maintaining the oxygen level near saturation in the surgery station livewell potentially resulted in higher blood oxygen levels during anesthesia, which aids in post-surgery recovery (Itazawa and Takeda 1982). Iwama and Ackerman (1994) suggested adding small amounts of salt to reduce gill irritation and help control blood hematology and chemistry.

Induction was attained within 3-5 minutes following immersion in the CO_2 bath. Anesthetized fish were removed from the immersion bath shortly after induction and placed in a wet fish-holding cradle. Each fish was inspected for anomalies (e.g., general condition of eyes, scales, and fins) and general health; unfit individuals were rejected for tagging. Surgical tag implantation began immediately after the fish was placed in the cradle and lasted approximately 2-3 minutes. During the first 2 minutes of surgery, fresh recovery water was occasionally flushed across the gill membranes to provide oxygen and remove metabolic wastes. After 2 minutes, freshwater was continuously flushed across gill membranes to facilitate rapid recovery.

Immediately after surgery was completed, fish were placed in PVC recovery tubes submerged in post-surgery livewells (identical to the fishing boat livewell) containing freshwater saturated with oxygen. The post-surgery livewells were located adjacent to the surgery station. Fish were removed from the recovery tubes after approximately 10 minutes but kept in the post-surgery recovery livewell for a total of 30 minutes. During this period, fish were observed closely for recovery progress and behavior. After 30 minutes, if the fish appeared to be fully recovered and exhibiting normal behavior, it was moved to an in-river livewell, and the extended recovery period began. The extended recovery period lasted for a minimum of 120 minutes. Fish were observed carefully during this period for recovery progress and behavior. After 120 minutes, when the fish was determined to be fully recovered and exhibiting normal behavior, it was released into the Sacramento River and the release time was noted.

Additional discussion on predator tagging procedures is presented in **Appendix C**. Additional discussion on the analysis of tagged predators and predation is presented in Section 3.7.

2.6 MONITORING AND DATA COLLECTION

This section describes the monitoring and data collection procedures.

2.6.1 ENVIRONMENTAL CONDITIONS MONITORING

Several variables were monitored during the study period to document environmental and other conditions that could influence the ultimate fate of the study fish. Each of these variables is discussed separately.

CLIMATE AND WEATHER

The California Irrigation Management Information System collects and manages data on general weather conditions (i.e., air temperature, precipitation, wind, and solar radiation) throughout California. A weather station is located at Twitchell Island (near Rio Vista, approximately 19 km southwest of the study area). Data collected over the study period were downloaded from the Twitchell Island station to represent climate and weather conditions over the study period (http://wwwcimis.water.ca.gov/Default.aspx).

SACRAMENTO RIVER AND GEORGIANA SLOUGH HYDROLOGY AND WATER QUALITY

The U.S. Geological Survey (USGS) maintains a network of flow monitoring and water quality gauges in the Sacramento River and Georgiana Slough. A gauge is located in the Sacramento River upstream from Walnut Grove (station SDC), in the Sacramento River below Georgiana Slough (station GES), and in Georgiana Slough at the Sacramento River (station GSS) (**Figure 2-5**). Data from these monitoring locations were used to characterize the hydrologic and water quality conditions in the study area throughout the study period. Information concerning each station is shown in **Table 2-2**. Hydrologic and water quality data were downloaded on July 30, 2012, from the California Data Exchange Center (DWR 2012). Stage, discharge, temperature, turbidity, and conductivity data were collected at 15-minute intervals from March 1, 2012, through May 31, 2012.

Table 2-2 Discharge and Water Quality Stations Close to the GSNPB Study Area			
Attribute	Station Code		
	SDC	GES	GSS
River basin	Sacramento River	Sacramento River	Sacramento River
Hydrologic area	Sacramento River	Sacramento River	Sacramento River
County	Sacramento	Sacramento	Sacramento
Nearby city	Walnut Grove	Walnut Grove	Walnut Grove
Operator	USGS	USGS	USGS
Elevation	10 feet	10 feet	10 feet
Latitude	38.257000°N	38.238900°N	38.237000°N
Longitude	121.518000°W	121.523400°W	121.518000°W
Full name	Sacramento River above DCC (above Georgiana Slough)	Sacramento River below Georgiana Slough	Georgiana Slough at Sacramento River
Source: California Data Exchange Center (DWR 2012)			

HYDRODYNAMICS

Two types of complementary hydrodynamic measurements were made to document the temporal evolution of the velocity field on the Sacramento River side of the BAFF. Measurements of the velocity fields within the Georgiana Slough/Sacramento River divergence were made using: 1) Eulerian (fixed position) sideward-looking acoustic Doppler current profilers (SL-ADCP's); and 2) in conjunction with DWR, Lagrangian measurements (i.e., drifters).

Eulerian Measurements

A total of six 600 kHz SL-ADCP'S were deployed along the BAFF face. The pilings were driven in locations and SL-ADCP's mounted in specific orientations to the flow to provide the maximum coverage under a variety of flow conditions. All of the SL-ADCP's were mounted on buoys attached to pilings (**Figure 2-9**). These buoys registered the SL-ADCP's (and hydrophones) at a fixed depth below the water surface. Fixing the SL-ADCP's on the water-surface-following buoys allowed for continuous monitoring of the surface currents, where salmon outmigrants typically reside (Blake and Horn, in press), under a broad range of Sacramento River flows and surface water elevation levels.

Lagrangian Measurements

In collaboration with DWR, the USGS documented the surface velocity field using surface-following drifters. These measurements were used to: 1) produce snapshots of surface current maps by interpolating velocities inferred from the drifter paths; and 2) calculate estimates of the location and shape of the critical streakline[3] at the divergence.

---

3 Critical streakline is the streamwise division of flow vectors entering each channel, i.e., the channel of the Sacramento River and the channel of Georgiana Slough.

When the flows were downstream and strongly uni-directional only a handful of drifter releases were made. However, during conditions where the flow field was substantially affected by the tides, drifters were deployed over an approximate 12-hour flood/ebb cycle to document a specific hydrologic condition (Sacramento River flow).

For downstream flowing conditions, a number of drifters were placed across the upstream section as quickly as this could be accomplished (over an approximate 5-10 minute period). Putting out the drifters rapidly is important because the velocity fields in junctions can change rapidly with the tides and it is preferred to have all of the drifters experience, as near as possible, the same conditions (this is one of the reasons the drifters used in this experiment are small). In space, the spacing between drifters released was decreased near the critical streakline so the position and shape of the critical streakline could be determined as accurately as possible. For converging flow conditions, drifters were deployed in the Sacramento River both upstream and downstream of the Georgiana Slough junction. Finally, for upstream flowing conditions, drifters were released downstream of the junction.

UNDERWATER LIGHT LEVELS

Continuous ambient light measurements were collected throughout the study period at the houseboat stationed at Dagmar's Marina (located on the right bank of the Sacramento River; **Figure 2-5**). The ambient light levels were collected to serve as representations of background light conditions occurring in the Sacramento River near the BAFF. Measurements were taken at a fixed 1-m depth below the water surface using LI-COR, Inc.'s LI-192SA light sensor and recorded using a LI-1400 data logger. Data were recorded in photosynthetic photon flux units and then manually converted to lux. Data values greater than 5.4 lux were considered to represent light conditions, whereas data with values less than 5.4 lux were representative of dark conditions. See Section 3.2 for additional discussion on underwater light levels.

BATHYMETRIC DATA

Bathymetric data were collected multiple times to map and record conditions on the riverbed during the study period. The frequency of bathymetric data collection was based on the variability and magnitude of flows during the study period, which could affect sediment transport and deposition processes.

2.6.2 BARRIER OPERATION MEASUREMENTS

Several variables were measured during the experiment to document conditions associated with BAFF operation that could influence the effectiveness of the barrier. Each of these variables is discussed separately.

UNDERWATER SOUND

Short-term sound measurements were collected at nine locations at various depths and distances from the BAFF. The project team had identified 10 locations for short-term sound measurements; however, short-term sound measurements could not be taken at one location (middle of river channel) because of strong currents and the lack of a safe anchor in the middle of the hydrophone array. Measurements were taken while the BAFF was on during night and daylight conditions on April 17, 2012, and April 18, 2012, respectively.

Short-term underwater noise levels were measured using a Larson Davis Model 831 precision integrating sound-level meter with a Teledyne Reson TC 4013 omnidirectional hydrophone. The sound-level meter was calibrated before and after use with G.R.A.S. Sound & Vibration A/S's pistonphone type 42AF to ensure that the measurements would be accurate. The sound-level meter and hydrophone were attached to a weighted bracket and lowered into the water from the work boat. Measurements were taken at depths ranging from 1 to 5 m below the water surface and distances ranging from 0 to 157 m from the BAFF. The sound-level meter was programmed to collect 10 individual interval files per second. An acoustic tag was fixed to the hydrophone to assist in recording the position at which measurements were taken in relation to the BAFF. A tape measure was used to make depth markings on the lowering rope to assist with determining the depth of measurements.

UNDERWATER LIGHT

Short-term light measurements were collected at eight locations at various depths and distances from the BAFF. Measurements were taken while the BAFF was on during daylight and night conditions on April 17, 2012, and April 18, 2012, respectively. Light was measured using Li-Cor, Inc.'s LI-192SA underwater quantum light sensor and recorded using a LI-1400 data logger. The light meter was attached to the end of a Teledyne Reson TC 4013 omnidirectional hydrophone, sound rod, and weighted bracket and lowered into the water from a boat. Measurements were taken at depths ranging from 1 to 5 m below the water surface and distances ranging from 0 to 157 m from the BAFF. An acoustic tag was fixed to the hydrophone to assist in recording the position at which measurements were taken in relation to the BAFF. A tape measure was used to assist with determining the depth of measurements. Light measurements were recorded as 15-second averages over a period of 1-2 minutes at each depth interval. Data were recorded in photosynthetic photon flux units and then manually converted to lux.

BUBBLE CURTAIN

The BAFF bubble curtain was monitored through daily checks of air pressure and flow (at a valve manifold feeding the air to the diffuser located at the staging area) and through visual inspections during the study period.

2.6.3 ACOUSTIC TAG DETECTION/MONITORING

As part of the barrier tests, a 3D monitoring system, composed of multiple hydrophones located in the river immediately upstream, downstream, and adjacent to the BAFF, was deployed and operated to monitor 3D fine-scale movement of tagged fish as they encountered and responded to the barrier. The upstream detection range of the array was the Walnut Grove Bridge, allowing determination of the movement of tagged fish into the study area. Acoustic detectors were positioned as part of the deployment of the BAFF, and monitored on-site, for use in documenting the response of tagged Chinook salmon and steelhead, and tagged predatory fish to the BAFF when it is on and when it is off. The hydrophone monitoring system also allowed on-site real-time detection and monitoring of movement by tagged fish into and through the study area. A detailed description of acoustic tag detection and monitoring is provided in the project data collection plan (**Appendix A**).

2.6.4 FISH FATES CLASSIFICATION AND ASSIGNMENT

To determine the fates of study fish (e.g., deterred, undeterred, eaten, etc.; see **Figures 2-12a** and **2-12b**), hydrophones were deployed to detect fish movement. MarkTag software was then used to build spatially referenced fish tracks, which were displayed in Eonfusion software (Myriax Software Pty Ltd.) for visual inspection and analysis of fish movement patterns and route selection. Fish tracks were systematically reviewed by the project team over an approximate week-long conference (August 20-24, 2012), referred to as the Fish Fates Conference. For all fish tracks, fish "fates" were determined for a total of seven different possible "events." The "events" were grouped into categories of entering the array, exiting the array, and predation. Each fate fish was assigned a fate code that was entered into a spreadsheet for further analysis. A schematic showing the categories of events, response, and fates (with fate codes) used during the conference is provided on **Figures 2-12a** and **2-12b**.

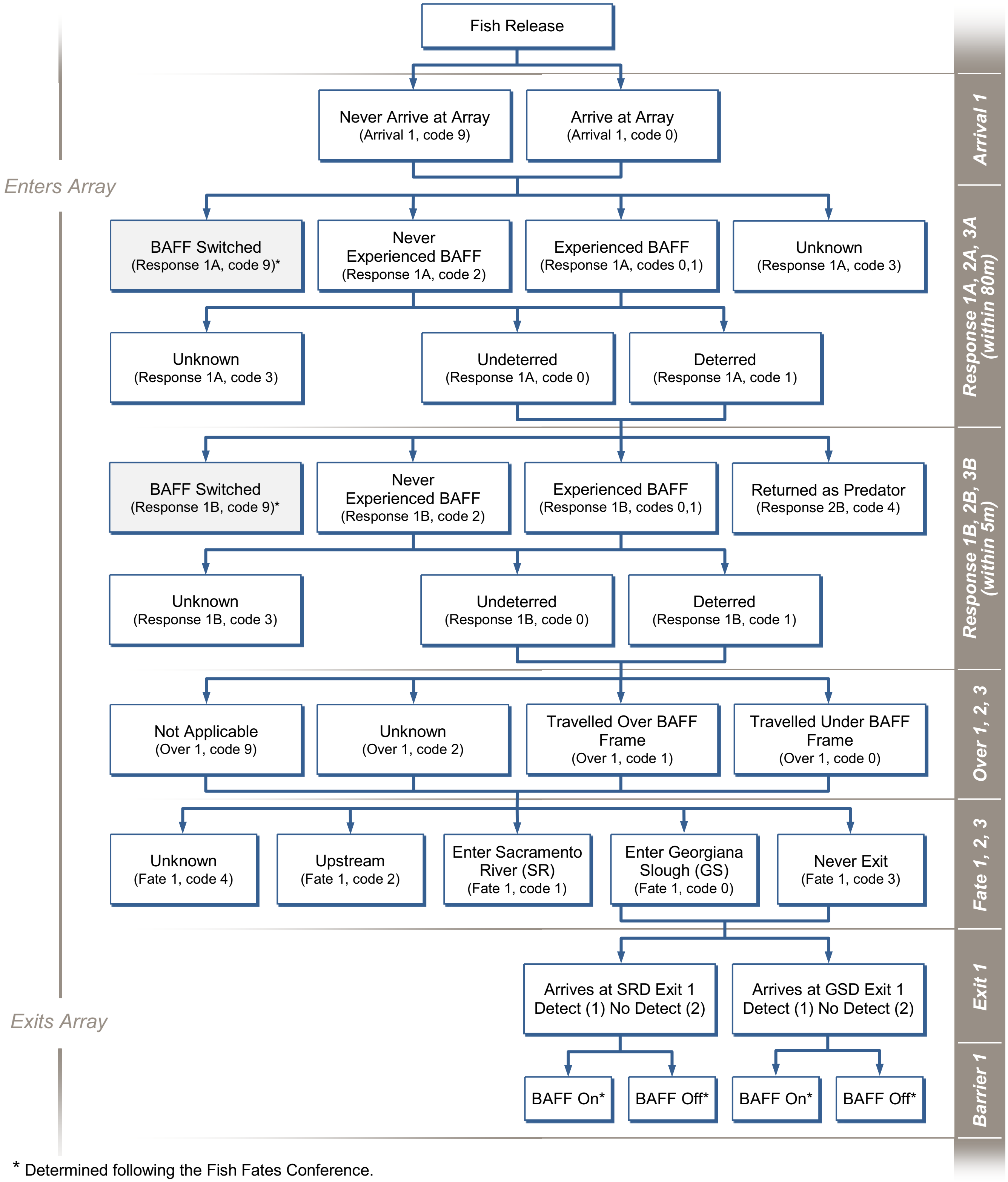


Figure 2-12a **Fish Fates Classification Schematic (Array Events)**

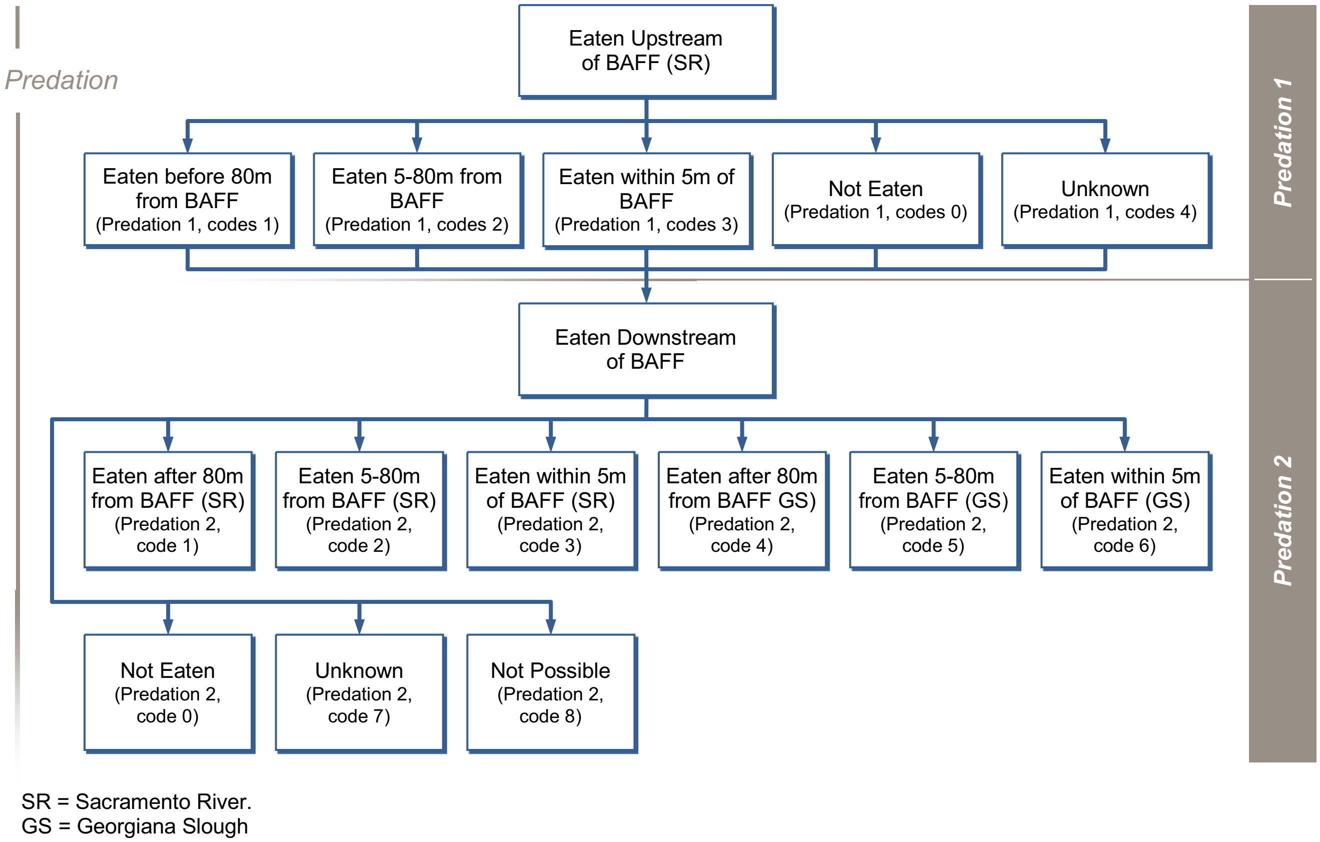


Figure 2-12b **Fish Fates Classification Schematic (Predation Events)**

2.6.5 ACTIVE HYDROACOUSTICS

Active hydroacoustics, several split-beam sonar units and a DIDSON camera, were used to detect and quantify predator-sized fish immediately adjacent to the barrier. At the start of the study (March 5, 2012), a series of Biosonics, Inc.'s DT-X split-beam transducers and a DIDSON unit were aligned to monitor the reach of the river near the BAFF. The active hydroacoustics were operated starting on March 6, 2012 and shut down on April 30, 2012 when disassembly of the BAFF began. See Section 3.7.4 for additional discussion of active hydroacoustics data analysis.

2.7 EXPERIMENTAL BARRIER OPERATIONS

The experimental barrier operations were designed to measure the responses of tagged juvenile Chinook salmon and steelhead migrating downstream in the Sacramento River that encounter Georgiana Slough when the BAFF is on or off over a range of discharge, tidal, and diel conditions. The selection of a starting BAFF setting (on or off) was chosen arbitrarily; the experiment began with the barrier in the "off" mode. Thereafter, the barrier was switched about every 25 hours on the minimum low tide. Switching the barrier operation about every 25 hours on the minimum low tide resulted in BAFF On and BAFF Off conditions over a range of light and tidal cycles; two full tidal cycles were completed every 25 hours.

BAFF On and BAFF Off operations are presented in **Table 2-3**. During the study observations were made routinely of BAFF operations. On several occasions, these observations suggested that the BAFF operations may have been impaired when an air nozzle appeared to become partially blocked and disrupted the continuity of the air bubble curtain. The study design and field observations allowed any potentially impaired BAFF operations to be identified and allowed statistical testing to determine whether deterrence, protection, and overall efficiency of the BAFF varied significantly between periods when the BAFF was on and operating routinely and periods when operations of the BAFF may have been impaired.

Table 2-3
2012 Georgiana Slough Study BAFF Operation

Date	BAFF On	BAFF Off	Duration (hours)
March 6, 2012	13:55		41:13:00
March 8, 2012		07:08	
March 9, 2012	08:12		22:59:00
March 10, 2012		07:11	
March 11, 2012	09:14		25:11:00
March 12, 2012		10:25	
March 13, 2012	10:45		24:43:00
March 14, 2012		11:28	
March 15, 2012	12:33		24:33:00
March 16, 2012		13:06	
March 17, 2012	14:16		24:33:00
March 18, 2012		14:49	
March 19, 2012	16:25		25:20:00
March 20, 2012		17:45	
March 21, 2012	18:39		25:04:00
March 22, 2012		19:43	
March 23, 2012	20:19		24:38:00
March 24, 2012		20:57	
March 25, 2012	22:55		23:46:00
March 26, 2012		22:41	
March 27, 2012	23:46		25:11:00
March 29, 2012		00:57	
March 30, 2012	02:02		24:51:00
March 31, 2012		02:53	

Table 2-3
2012 Georgiana Slough Study BAFF Operation

Date	BAFF On	BAFF Off	Duration (hours)
April 1, 2012	04:17		24:28:00
April 2, 2012		04:45	
April 3, 2012	05:39		24:08:00
April 4, 2012		05:47	
April 5, 2012	06:27		24:03:00
April 6, 2012		06:30	
April 7, 2012	06:58		24:57:00
April 8, 2012		07:55	
April 9, 2012	09:29		23:52:00
April 10, 2012		09:21	
April 11, 2012	10:05		24:15:00
April 12, 2012		10:20	
April 13, 2012	10:14		26:51:00
April 14, 2012		13:05	
April 15, 2012	13:30		25:31:00
April 16, 2012		15:01	
April 17, 2012	16:14		24:34:00
April 18, 2012		16:48	
April 19, 2012	18:59		24:01:00
April 20, 2012		19:00	
April 21, 2012	20:22		25:18:00
April 22, 2012		21:40	
April 23, 2012	21:50		25:34:00
April 24, 2012		23:24	
April 25, 2012	23:09		25:20:00
April 27, 2012		00:29	
April 28, 2012	01:15		24:47:00
April 29, 2012		02:02	

3 ANALYSIS METHODS, RESULTS AND DISCUSSION

This chapter describes methods, results, and discussion of the different analyses conducted as part of the 2012 GSNPB Study. The following evaluation metrics of BAFF performance were compared between BAFF On and BAFF Off conditions using the results of acoustic tracking:

- barrier efficiency (see Section 3.2), which is evaluated by three metrics:
  - deterrence efficiency: the proportion of tagged juvenile salmonids encountering the BAFF that were deterred from entering Georgiana Slough and instead migrated down the Sacramento River;
  - protection efficiency: the proportion of tagged juvenile Chinook salmon and steelhead that survived to the BAFF avoiding predation while migrating down the Sacramento River, past the BAFF;
  - overall efficiency: the proportion of tagged juvenile Chinook salmon and steelhead that were released and were detected in the study area immediately upstream from the BAFF that subsequently were detected successfully migrating downstream in the Sacramento River, accounting for losses of fish migrating into Georgiana Slough and predation losses in the area where the array is located adjacent to the BAFF (see **Figure 2-1**); and
- survival and route entrainment probabilities (see Section 3.3): model predictions of fish survival from one location to another based on mark and recapture.

Several additional analyses were used to evaluate and identify potential relationships between barrier operations, barrier effectiveness, fish responses, and other factors, whereas others were conducted to further evaluate and improve approaches and procedures used in conducting data processing and analysis. The following additional analyses were conducted:

- fish track processing and development (see Section 3.1): a comparison and evaluation of different fish track processing and development methodologies;
- analysis of hydrodynamics and critical streakline (see Section 3.4): high-resolution analysis and mapping of hydrodynamics and identification of the critical streakline (the location of the flow split) in the study array;
- spatial analysis of fish distribution (see Section 3.5): data processing and analysis of the spatial distribution of fish in relation to a number of factors, including water velocity, light/dark conditions, and barrier operations;
- generalized linear modeling of tagged fish fates (see Section 3.6): model predictions of tagged fish fates based on several factors, including BAFF operation and environmental conditions;
- analysis of predators and predation (see Section 3.7): analysis of predators and predation on juvenile salmonid study fish in the array related to barrier presence and operational condition (BAFF On/Off), in addition to other factors; and

- analysis of 2011 Delta-wide survival (see Section 3.8): data processing and analysis of 2011 telemetry-based outmigration data to estimate survival of fish as they migrate through different channels throughout a larger, Delta-wide region.

A full description of the methods, results, and discussion for each of the different analyses follow.

3.1 FISH TRACK PROCESSING AND DEVELOPMENT

Evaluating the performance of the BAFF at the Georgiana Slough on fish behavior required generating and analyzing multi-dimensional tracks of the acoustically-tagged fish as they moved through the study area. The multi-dimensional tracks used in the analysis are the product of a complex combination of hardware that filters and records underwater acoustic signals, advanced signal processing software that separates tag echoes from acoustic noise, and tag tracking software that uses applied numerical methods to estimate the location of the acoustic tags that produce these signals (see Section 2.6 and **Appendix A** for additional discussion). The process of turning acoustic signals into multi-dimensional fish tracks is not a simple pre-processing step in the research process, but rather, an integral part of the study with many steps that require parameterization and design decisions that significantly affect the end product. In the past, it has been difficult to ascertain how much influence these decisions have on the overall study analysis, because investing the amount of time required to completely reprocess the data from a large tracking study with multiple parameter sets has not been possible. The 2012 GSNPB Study presented a unique opportunity to explore the effects of different echo-selection and tag-positioning methodologies in the context of a multi-dimensional fish passage analysis. This study allowed for the use of two different approaches: 1) use of the USGS's FishCount and GeneticFish algorithms; and 2) use of HTI's MarkTags and AcousticTag software to develop fish tracks (or paths). These two approaches were evaluated to determine how different methodologies can be used to generate and analyze multi-dimensional tracks of the acoustically-tagged fish.

To explore the performance of different echo selection and acoustic tag positioning algorithms, a subset of tag codes were processed multiple times using different technology combinations. This resulted in three sets of tag tracks that were used for the tag comparison analysis:

- Group 1 Tracks: a set of tracks produced using HTI's MarkTags software for echo selection, and AcousticTag software for tag positioning;

- Group 2 Tracks: a set of tracks produced using the USGS's FishCount algorithm for echo selection and HTI's AcousticTag software for tag positioning; and

- Group 3 Tracks: a set of tracks produced using the USGS's FishCount algorithm for echo selection, and the USGS's GeneticFish algorithm for tag positioning.

This combination of echo selection and tag positioning approaches allowed the effects of echo selection on tracking (Group 1 Tracks compared to Group 2 Tracks) and the effects of different tracking methodologies using the same echo selection (Group 2 tracks versus Group 3 tracks) to be examined.

The subset of tags used for this comparison included 291 uniquely coded tags that had been surgically implanted in Chinook salmon and steelhead (see Section 2.5.3) or attached to drifters that were allowed to float through the study area. Four additional tags were suspended underneath a small floating platform outfitted with a real-time kinematic (RTK) antenna and pulled behind a boat through the study area. Quantitative comparisons were made between the three different groups of tracks for each of the 291 fish tags, and the overall distribution of differences between the tracks for each of these groups was examined for each metric used to evaluate the different technologies. The tracks for the RTK tags were analyzed separately by comparing the tracks of the RTK tags to the tracks generated by the GPS signal collected by the RTK antenna.

The echo quality and quantity metrics analyzed for the 291 fish tag tacks suggest that performing echo selection with FishCount will result in a slight degradation in track quality, with quantitative measures of track quality decreasing on the order of a few percentage points. If reductions in data processing cost and data turnaround time can be achieved using FishCount to automate echo selection on cloud computing platforms, then these benefits should be weighed against the risk of a slight decrease in track quality when designing future studies. Additional details, including methods, results, discussion, and recommendations are provided in **Appendix E**.

3.2 BARRIER DETERRENCE, PROTECTION, AND OVERALL EFFICIENCY

3.2.1 METHODS

The efficiency of the BAFF was tested by releasing tagged juvenile Chinook salmon and steelhead at a location upstream of the BAFF and monitoring the migration pathway of each fish as it passed through the hydrophone arrays. Based on acoustic tag tracking results for juvenile Chinook salmon and steelhead that entered the study area and encountered the BAFF, estimates were derived for deterrence efficiency, protection efficiency, and overall efficiency by comparing results for fish passing through the array when the BAFF was on and when it was off. Some Chinook salmon and steelhead were classified as eaten by predatory fish based on changes in the characteristics of their acoustic tag track. Tracks of juvenile Chinook salmon and steelhead passing through the array were typically unidirectional in a downstream pathway, whereas tracks for Chinook salmon and steelhead presumably eaten by a predator typically showed little movement or erratic pathways that included upstream movement, and the vast majority of movement occurred along the river margin. To account for predation of juvenile Chinook salmon and steelhead, protection efficiency was calculated to account only for those acoustic tag tracks characterized as those of fish not eaten by a predator. As a result, comparing protection efficiency with overall efficiency provides an indicator of predation effects on BAFF efficiency.

The experimental design and data collection associated with the 2012 evaluation of the performance efficiency of the BAFF included comparisons of results under the following conditions: 1) time periods when the BAFF was on and off and there was no evidence that BAFF operations had been potentially compromised by variation in the bubble curtain or other operations; 2) time periods when the BAFF was on and off under light conditions defined as dark [low light < 5.4 lux] and light [high light ≥ 5.4 lux]); and 3) time periods when the BAFF was on and off when water velocity passing through the BAFF was low (< 0.25 m/s) and high (≥ 0.25 m/s).

The criterion used for characterizing light and dark ambient conditions was based on the work of Anderson et al. (1988), which showed that Chinook salmon exhibit an avoidance reaction to strobe lights at a threshold between 5.4 and 27 lux. As a result, it was assumed that if the ambient light is greater than the lower threshold, then the ambient light may influence the BAFF's ability to initiate a reaction to the HIMLs. No known study with steelhead could be located with which to improve on the threshold specific to *O. mykiss*. Thus, the same criterion used for Chinook salmon (5.4 lux) was used for steelhead.

As described in Chapter 2, during the study period observations of BAFF operations were made routinely. On several occasions, these observations suggested that the BAFF operations may have been impaired when an air nozzle became blocked and disrupted the continuity of the air bubble curtain or when other operational issues arose. The study design and field observations allowed any potentially impaired BAFF operations to be identified and to allow statistical testing to determine whether or not deterrence, protection, and overall efficiency of the BAFF varied significantly between periods when the BAFF was on and operating routinely and periods when operations of the BAFF may have been impaired.

A single "sample" was a period during which: 1) the BAFF state (on or off) did not change; 2) light did not cross the threshold level (5.4 lux); and 3) the approach velocity did not cross the threshold level (0.25 m/s). All tagged fish that passed through the array during a single sample period were used to calculate deterrence, protection, and overall efficiency for that sample. A new sample was made when one of the three variables changed.

Estimates of BAFF efficiency (deterrence, protection, and overall efficiency) were calculated for Chinook salmon and steelhead. Additional analysis comparing Chinook salmon with steelhead, 2011 Chinook to 2012 Chinook, and BAFF efficiency under additional covariates were also conducted. Equations used to calculate deterrence, protection, and overall efficiency are presented in Section 2.3.

3.2.2 RESULTS

CHINOOK SALMON

The sample sizes for Chinook salmon for when the BAFF was off, when the BAFF was on, and when the BAFF was potentially impaired are summarized in **Tables 3.2-1** and **3.2-2**. Of the 1,501 Chinook salmon that were tagged and released, a total of 1,423 passed within 80 m of the BAFF (the sound field where fish reaction would be expected). The number of fish found in these samples ranged from 2 to 19. Based on the results of these analyses, subsequent statistical analyses were performed to evaluate BAFF deterrence, protection, and overall efficiency over the range of environmental conditions that occurred during the study to assess BAFF efficiency as a function of ambient light levels and water velocities passing through the BAFF.

The initial statistical testing focused on testing the hypotheses that there was no significant difference in deterrence, protection, and overall efficiency of the BAFF when it was on and when it was off. The initial comparison disregarded observations made when the BAFF was potentially impaired. Results of initial parametric statistical analysis showed that the basic assumptions of the parametric tests were not met; therefore, the subsequent statistical analyses were based on nonparametric comparisons (i.e., Kruskal-Wallis Test). The first analysis compared deterrence efficiency, protection efficiency, and overall efficiency using observations when the BAFF was on (and fully functional) and off.

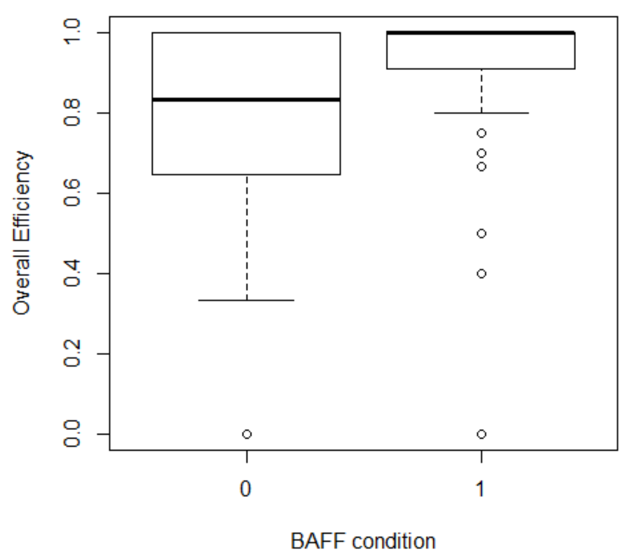
Table 3.2-1
Summary of Tagged Chinook Salmon Samples Encountering the BAFF during On and Off Operations at Low (< 5.4 Lux) and High (≥ 5.4 Lux) Light Levels

Light Level	BAFF Off (N)	BAFF On (N)	BAFF Potentially Impaired (N)
Low light	57	42	12
High light	57	44	9
Total	114	86	21

Table 3.2-2 Summary of Tagged Chinook Salmon Samples Encountering the BAFF during On and Off Operations at Low (< 0.25 m/s) and High (≥ 0.25 m/s) Approach Velocities			
Approach Velocity Level	**BAFF Off (N)**	**BAFF On (N)**	**BAFF Potentially Impaired (N)**
Low water velocity	100	75	18
High water velocity	14	11	3
Total	114	86	21

A significantly greater deterrence efficiency, protection efficiency, and overall efficiency was found under BAFF On operations than under BAFF Off operations (**Table 3.2-3**).The BAFF On operations resulted in consistently greater deterrence (15.2 percentage point improvement), protection (14.4 percentage point improvement), and overall efficiency (14.5 percentage point improvement) than the BAFF Off operations. This result showed there was a statistically measurable difference (represented by P-values below critical alpha value of 0.05) in performance when the BAFF was on than when it was off (**Table 3.2-3**). The distribution of deterrence efficiency for BAFF On and BAFF Off shows a great deal of overlap in range (**Figure 3.2-1**).

Table 3.2-3 Comparison of BAFF On and Off Operations for Three Chinook Salmon Response Metrics: Deterrence Efficiency, Protection Efficiency, and Overall Efficiency					
Comparison Metrics	**BAFF On Mean**	**BAFF Off Mean**	**Percentage Point Change in Efficiency**	**Kruskal-Wallis X^2**	**P-value**
Deterrence efficiency	0.561	0.409	15.2	11.256	0.0008
Protection efficiency	0.890	0.746	14.4	15.363	<0.0001
Overall efficiency	0.897	0.752	14.5	21.653	<0.0001



Note: Observations of potentially impaired BAFF operations were not included. BAFF On is represented as 1, and BAFF Off is represented as 0. The lower line of each box represents the 25th percentile of observations, whereas the upper line represents the 75th percentile. The lower whisker represents the 10th percentile, and the upper whisker represents the 90th percentile.

Figure 3.2-1Distribution of Overall Efficiency during BAFF On and Off Operations for Chinook Salmon

The numerators of protection and overall efficiency include all tagged Chinook salmon that reached the downstream Sacramento River hydrophones (see Hydrophones 5 and 6 on **Figure 2-1**). It is possible that some Chinook salmon passed by the BAFF at a distance of more than 80 m and were included in the numerators of protection and overall efficiency. However, protection and overall efficiency are designed to provide a measure of the total number of salmonids passing by Georgiana Slough and remaining in the Sacramento River. Deterrence efficiency provided the contribution of the BAFF's operation (through deterrence) to the overall efficiency.

The influence of the BAFF on fish passing more than 80 m from the BAFF was also investigated. It was estimated that this scenario could possibly have occurred for a total of 36 tags. The inclusion of these fish would increase the protection and overall efficiency values; however, the effect of this increase would be minor because a total of 1,423 tags were used for the hypotheses testing. It should be emphasized that the analysis of overall efficiency included these fish because this metric is intended to show the total number of tagged juvenile salmonids that move successfully through the study area.

After it was determined that the deterrence efficiency with BAFF Off was significantly less than with BAFF On, the influence of light on deterrence efficiency was investigated. Light conditions were divided into two categories: dark (< 5.4 lux) and light (≥ 5.4 lux). During dark periods, deterrence efficiency was found to be significantly less during BAFF Off operations than during BAFF On operations (**Table 3.2-4**). Deterrence efficiency in the light was found to be significantly less during BAFF Off operations than during BAFF On operations (**Table 3.2-4**). Protection and overall efficiency also improved when the BAFF was on under both low and high light conditions (**Table 3.2-4**). P-values were below the critical alpha value (0.05) for all metrics with the exception of protection efficiency (p=0.0758) and overall efficiency (p=0.0544) under low light.

Table 3.2-4
Comparisons of Deterrence, Protection, and Overall Efficiencies for Chinook Salmon during BAFF On and Off Operations under Low (< 5.4 Lux) and High (≥ 5.4 Lux) Light Levels

Comparison Metrics	BAFF On Mean	BAFF Off Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X^2	P-value
Deterrence efficiency—low light	0.492	0.344	14.8	6.419	0.0113
Deterrence efficiency—high light	0.628	0.473	15.5	5.288	0.0215
Protection efficiency—low light	0.842	0.728	11.4	3.153	0.0758
Protection efficiency—high light	0.937	0.766	17.1	14.723	0.0001
Overall efficiency—low light	0.842	0.739	10.3	3.701	0.0544
Overall efficiency—high light	0.950	0.765	18.5	22.330	<0.0001

When the approach velocity was < 0.25 m/s, deterrence efficiency was significantly lower when the BAFF was off compared to when it was on (**Table 3.2-5**). Similarly, when the approach velocity was ≥ 0.25 m/s, deterrence efficiency was significantly lower when the BAFF was off compared to when the BAFF was on (**Table 3.2-5**). The same pattern was observed for protection and overall efficiencies; both protection and overall efficiencies improved significantly when the BAFF was on compared to when it was off. P-values were well below the critical alpha value (0.05) for all metrics. The overall efficiency of 0.942 (94.2 percent efficiency) when the BAFF was on under low-velocity conditions (**Table 3.2-5**) was among the highest levels of overall efficiency for juvenile salmonids detected for BAFF operations conducted to date. For example, the highest overall efficiencies ever recorded were 92.7 percent observed in BAFF tests on the River Leven, Cumbria, United Kingdom (Turnpenny and O'Keefe 2005), 97.7 percent in one trial in Ragitata River, Central South Island Region, New Zealand (Webb 2011), and 80 percent on the River Frome, Dorset, United Kingdom (Beaumont, pers. comm., 2011).

Table 3.2-5
Comparisons of Deterrence, Protection, and Overall Efficiencies for Chinook Salmon during BAFF On and Off Operations under Low (< 0.25 m/s) and High (≥ 0.25 m/s) Approach Velocities

Comparison Metrics	BAFF On Mean	BAFF Off Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X^2	P-value
Deterrence efficiency—low velocity	0.573	0.456	11.7	7.287	0.0069
Deterrence efficiency—high velocity	0.485	0.071	41.4	7.797	0.0052
Protection efficiency—low velocity	0.945	0.836	10.9	15.081	0.0001
Protection efficiency—high velocity	0.515	0.107	40.8	6.251	0.0124
Overall efficiency—low velocity	0.942	0.823	11.9	19.603	<0.0001
Overall efficiency—high velocity	0.591	0.179	41.2	4.724	0.0298

It was unexpected that one of the greatest advantages of the BAFF is its effectiveness in velocities higher than the design velocity (0.25 m/s). In the periods when velocities exceeded 0.25 m/s, BAFF operations improved both protection and overall efficiency by more than 40 percentage points.

Deterrence, protection, and overall efficiencies were all significantly greater over a wide range of ambient light and water velocity conditions when the BAFF was on compared to when it was off (**Tables 3.2-4** and **3.2-5**). Thus, it may be concluded that operating the BAFF improved deterrence, protection, and overall efficiencies during both day and night conditions and under both low and high water velocities.

Potential impairments to BAFF routine operations were evaluated statistically by comparing deterrence, protection, and overall efficiencies of the BAFF during periods when the BAFF was on and operating routinely and periods when BAFF operations were potentially compromised. Results of these analyses detected no statistically significant difference between operations for deterrence or protection efficiency (**Table 3.2-6**). The percentage point differences in mean deterrence and protection efficiencies were less than 11. In addition, the deterrence and protection efficiency estimates during the period when BAFF operations were potentially compromised were lower than estimates for periods when BAFF operations were not potentially compromised. Because no significant difference was found in deterrence and protection efficiency, results were subsequently pooled to redo the above statistical analyses for observations of juvenile Chinook salmon passage during periods when the BAFF was operating routinely and when BAFF operations were potentially compromised.

In addition to deterrence and protection efficiency, potential impairments to BAFF operations were evaluated statistically for overall efficiency of the BAFF during periods when the BAFF was on and operating routinely and periods when BAFF operations were potentially compromised. Results of this analysis detected a difference that was great enough to produce a near-statistically significant (p=0.0652) difference between operations for overall efficiency (**Table 3.2-6**). Thus, periods when the BAFF was on and operating routinely and periods when BAFF operations were potentially compromised were not pooled for overall efficiency statistical tests.

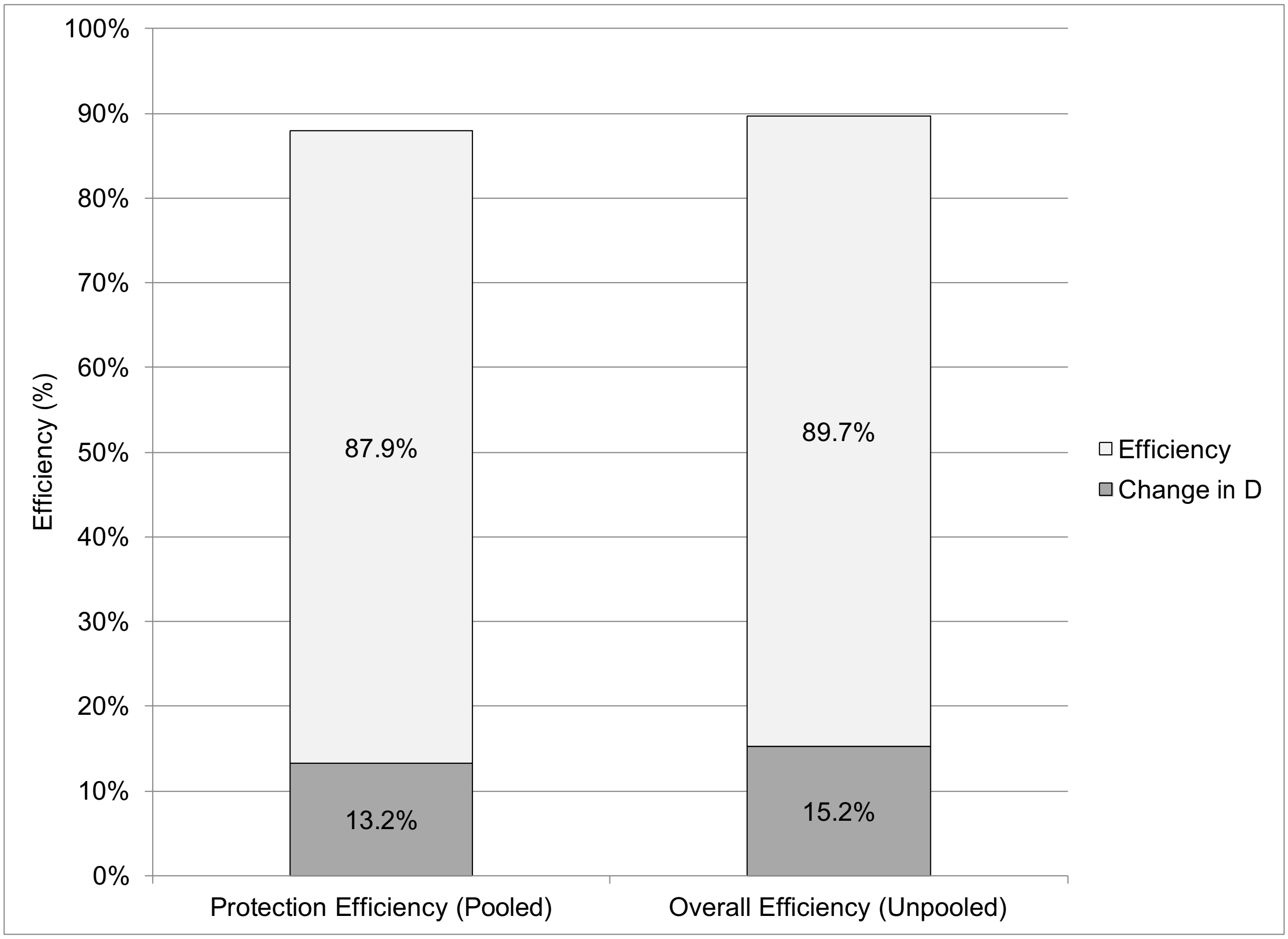
Table 3.2-6
Comparison of Deterrence, Protection, and Overall Efficiencies for Chinook Salmon during BAFF On and BAFF Potentially Impaired Operations

Comparison Metrics	BAFF On Mean	BAFF Impaired Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X^2	P-value
Deterrence	0.561	0.455	10.6	2.091	0.1482
Protection	0.890	0.835	5.5	1.065	0.3021
Overall	0.897	0.812	8.5	3.400	0.0652

For the pooled data, significantly greater deterrence and protection efficiencies were found when the BAFF was on (fully functional and potentially impaired pooled) compared to periods when the BAFF was off (**Table 3.2-7**). In addition, the pooled protection efficiency data showed high protection efficiencies (near 88 percent), whereas the contribution of the BAFF operation was about 13 percentage points (**Figure 3.2-2**). In addition, the unpooled overall efficiency data showed a high efficiency (near 90 percent), whereas the contribution of the BAFF operation was about 15 percentage points (**Figure 3.2-2**). The contribution of the BAFF operation to protection and overall efficiency is determined by the difference between deterrence efficiencies with BAFF On and BAFF Off (**Figure 3.2-2**, **Tables 3.2-3** and **3.2-6**).

The change in deterrence efficiency shows the improvement in deterrence when the BAFF was on compared to when it is off. It is the observable effect on fish behavior in response to operation of the BAFF. The change in deterrence efficiency was the contribution the BAFF made to the overall efficiency, the total proportion of tagged fish that continued down the Sacramento River (**Figure 3.2-2**). If all fish that were eaten in the vicinity of Georgiana Slough are removed from the evaluation of overall efficiency, these “salmonid-only” observations are used to calculate protection efficiency. If protection and overall efficiency are similar, it may be concluded that the effect of predation was slight. This is, in fact, the case (**Figure 3.2-2**, **Table 3.2-3**, and **Table 3.2-6**). If predation was high, and fish migrate through while the predators tend to remain in the study area, then protection and overall efficiency would be very different.

Using the pooled data, the study team compared deterrence and protection efficiencies for BAFF Off and BAFF On operations for observations obtained during dark periods (ambient light < 5.4 lux). Both response variables were significantly lower with the BAFF Off compared to when it was On (**Table 3.2-8**). Both response variables were also compared at BAFF Off to BAFF On operations for observations made during high light periods (ambient light ≥ 5.4 lux). Similar to observations obtained in the dark, deterrence and protection efficiencies were found to be significantly lower during periods when the BAFF was off compared to periods when it was on (**Table 3.2-9**). For each light level, the contribution of the BAFF operations to overall efficiency can be seen graphically in **Figure 3.2-3**. In both low and high light conditions, 84-95 percent of the fish pass down the Sacramento River, and the change in deterrence efficiency caused by the operation of the BAFF contributes about 15 percentage points.



Note: The change in deterrence efficiency (D) is the difference in deterrence efficiency between BAFF On and BAFF Off operations. The observations of BAFF On operations and the BAFF potentially impaired operations are pooled for the protection efficiency calculation.

Figure 3.2-2 **Relative Contribution of the BAFF Operations to Deterrence and Protection Efficiency for Chinook Salmon**

Table 3.2-7
Comparison of Deterrence and Protection Efficiencies for Chinook Salmon during BAFF On and BAFF Potentially Impaired (Pooled) and BAFF Off Operations

Comparison Metrics	Pooled BAFF On Mean	BAFF Off Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X^2	P-value
Deterrence	0.541	0.409	13.2	9.529	0.0020
Protection	0.879	0.746	13.3	14.859	0.0001

Table 3.2-8
Comparison of Overall Efficiencies for Chinook Salmon during BAFF On, BAFF Potentially Impaired, and BAFF Off Operations

BAFF State	Mean	Statistical Grouping
BAFF On	0.897	a
BAFF potentially impaired	0.812	ab
BAFF Off	0.752	b

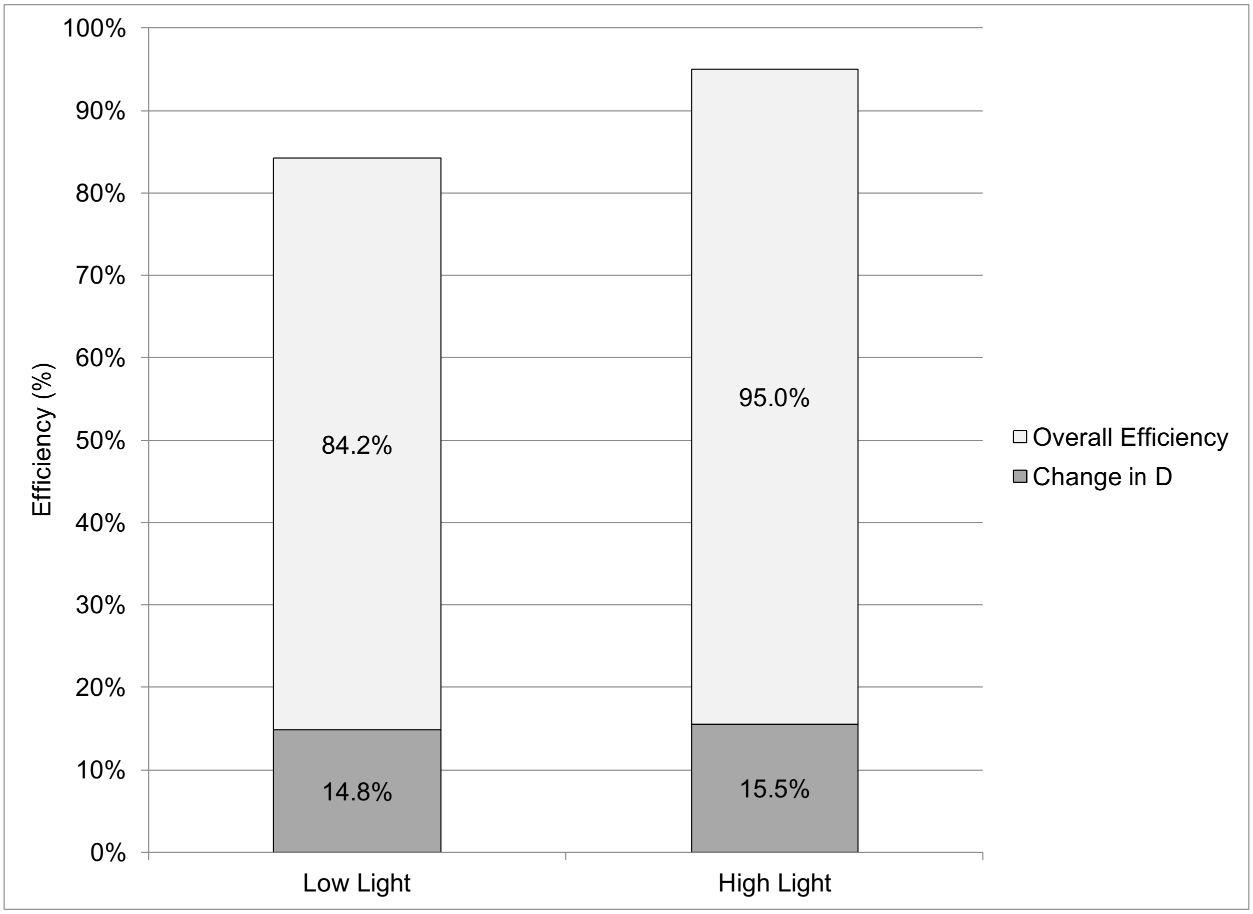
Note: "Statistical grouping" indicates samples are statistically similar by assigning them the same lowercase letter.

Table 3.2-9
Comparisons of Deterrence, Protection, and Overall Efficiencies for Chinook Salmon during BAFF On and BAFF Potentially Impaired (Pooled) and BAFF Off Operations under Low (< 5.4 Lux) and High (≥ 5.4 Lux) Light Levels

Comparison Metric	Pooled BAFF On Mean	BAFF Off Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X2	P-value
Deterrence efficiency—low light	0.473	0.344	12.9	5.909	0.0151
Deterrence efficiency—high light	0.609	0.473	13.6	4.473	0.0344
Protection efficiency—low light	0.847	0.728	11.9	3.883	0.0488
Protection efficiency—high light	0.912	0.766	14.6	12.938	0.0003

Note: Overall efficiency results by light level can be found in **Table 3.2-4**.

When the approach velocity was < 0.25 m/s, deterrence and protection efficiencies were significantly lower during periods when the BAFF was off compared to periods when it was fully functional or potentially impaired (**Table 3.2-10**). Similarly, when the approach velocity was ≥ 0.25 m/s, deterrence and protection efficiencies were significantly lower during periods when the BAFF was off compared to periods when it was fully functional or potentially impaired (**Table 3.2-10**). For each velocity level, the contribution of the BAFF operations to overall efficiency can be seen graphically (**Figure 3.2-4**). Unlike the contributions made during different light periods, contributions vary between low- and high-velocity conditions. Under high-velocity conditions, a smaller percentage of fish pass down the Sacramento River, and the change in deterrence efficiency caused by BAFF operations contributes a larger percentage than under low-velocity conditions. A considerable improvement was observed for pooled Chinook salmon protection efficiency at high velocities. Of the 46.4 percent of Chinook salmon that were protected, 35.7 percentage points of that was attributable to BAFF operations (**Table 3.2-10**).



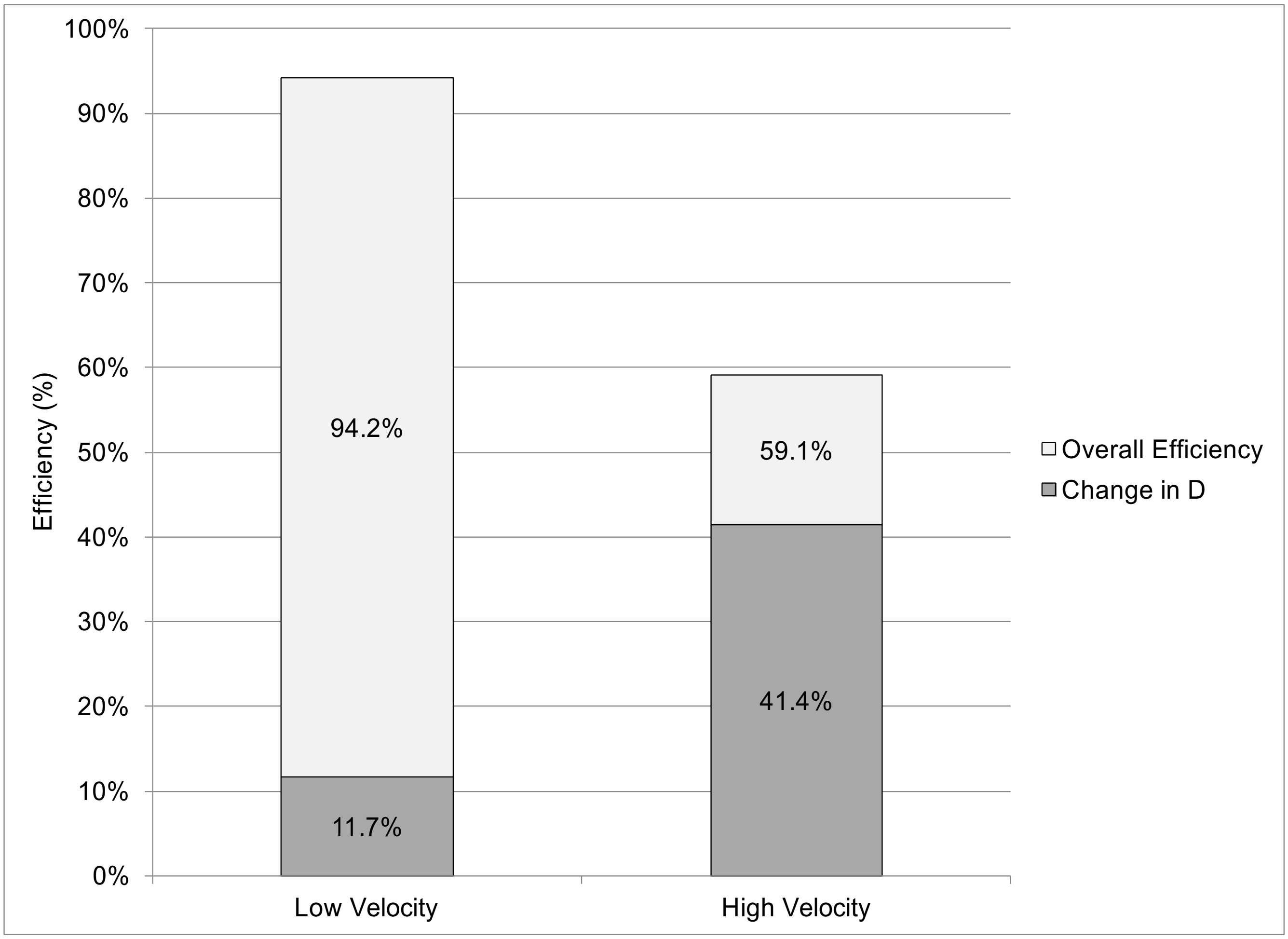
Note: The change in deterrence efficiency (D) is the difference in deterrence efficiency between BAFF On and BAFF Off operations.

Figure 3.2-3 **Relative Contribution of the BAFF Operations to Overall Efficiency for Chinook Salmon under Different Light Conditions**

Table 3.2-10
Comparisons of Deterrence, Protection, and Overall Efficiencies for Chinook Salmon during BAFF On and BAFF Potentially Impaired (Pooled) and BAFF Off Operations under Low (< 0.25 m/s) and High (≥ 0.25 m/s) Across-Barrier Water Velocities

Comparison Metric	Pooled BAFF On Mean	BAFF Off Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X^2	P-value
Deterrence efficiency—low velocity	0.559	0.455	10.4	6.383	0.0115
Deterrence efficiency—high velocity	0.416	0.071	34.5	6.844	0.0089
Protection efficiency—low velocity	0.942	0.836	10.6	16.130	<0.0001
Protection efficiency—high velocity	0.464	0.107	35.7	6.462	0.0110

Note: Overall efficiency results by water velocity can be found in **Table 3.2-5**.

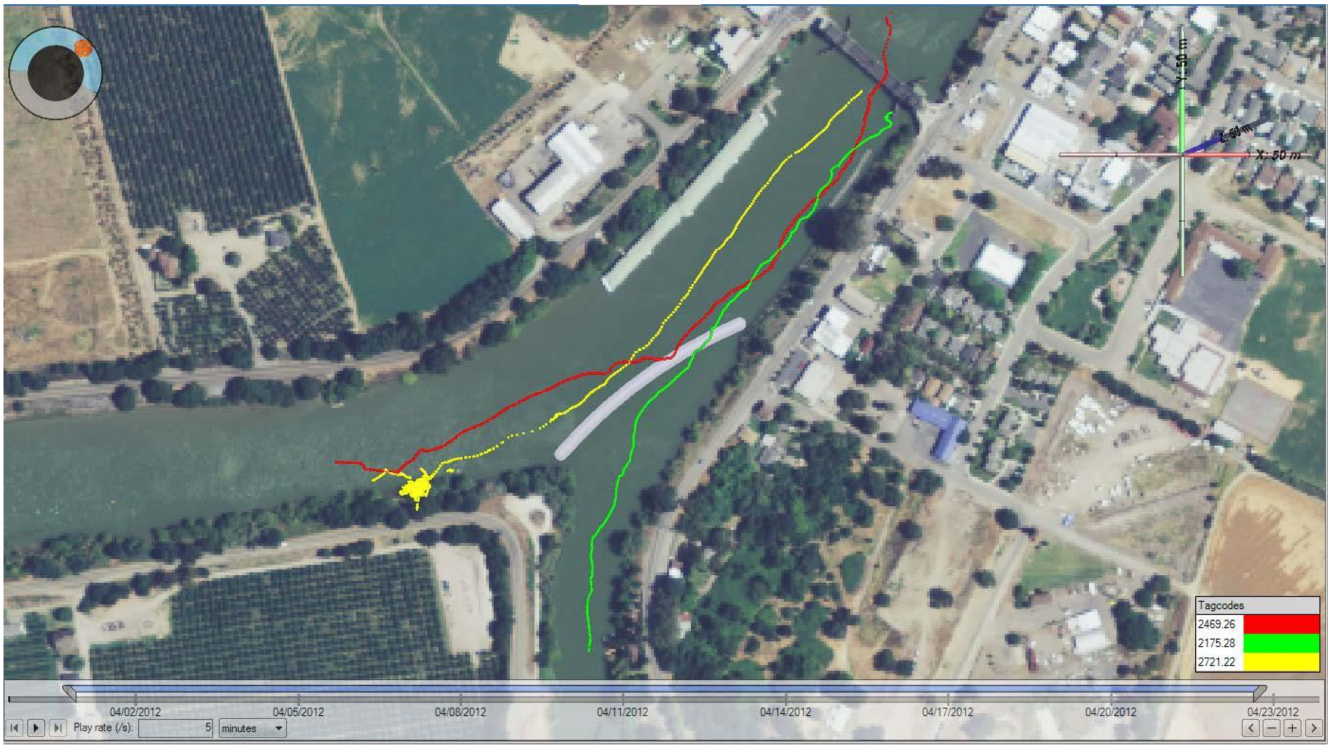


Note: The change in deterrence efficiency (D) is the difference in deterrence efficiency between BAFF On and BAFF Off operations.

Figure 3.2-4 Relative Contribution of the BAFF Operations to Overall Efficiency (Unpooled Data) for Chinook Salmon under Different Velocity Conditions

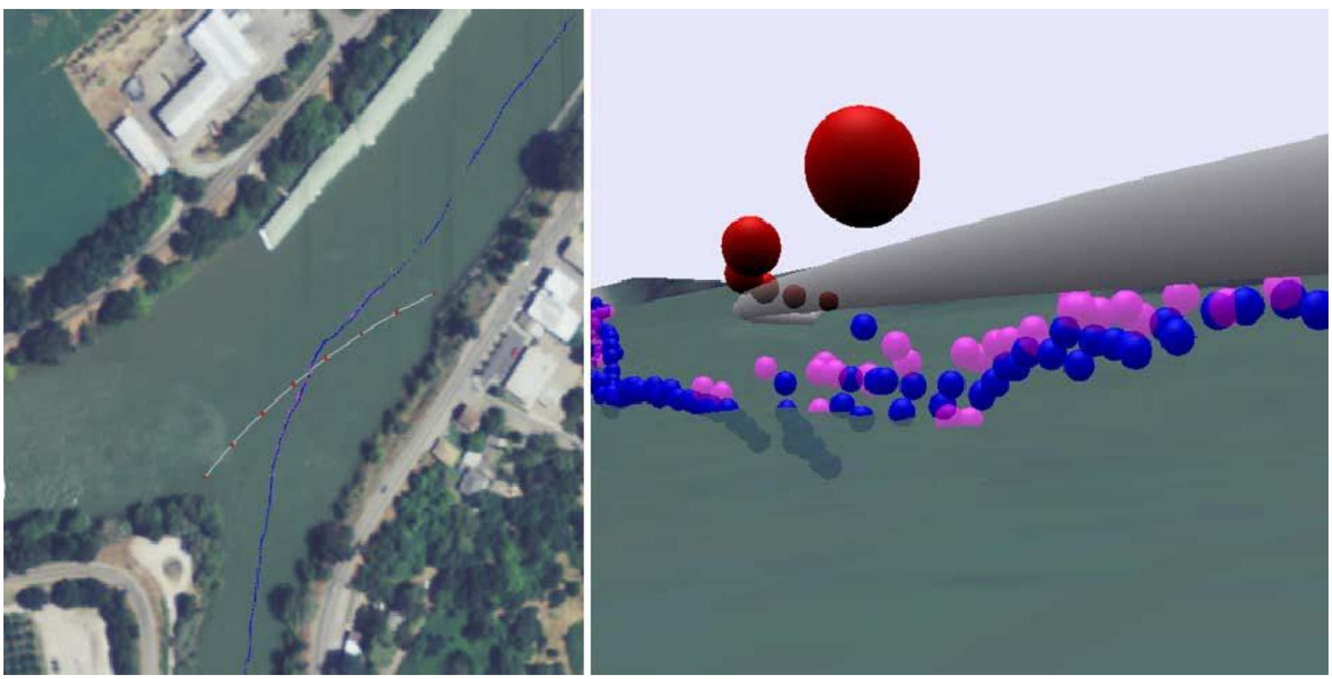
Two-dimensional tracks were developed for each tagged juvenile Chinook salmon as it migrated downstream in the Sacramento River and encountered Georgiana Slough and the BAFF (**Figure 3.2-5**). These tracks were analyzed by teams at the Fish Fates Conference, where classifications of predation on the tagged fish, or lack thereof, and deterrence were made. The deterrence and predation classifications and the 2D tracks provided a basis for examining individual fish responses to the BAFF as a function of water velocity and distance from the BAFF. For those fish that passed through the BAFF into Georgiana Slough, 3D tracking allowed for an assessment of the tag's location (depth) within the water column in order to determine if the tag (and fish) went over or under the BAFF. **Figure 3.2-6** shows an example of a 3D map using two different tracking methods of a tagged juvenile Chinook salmon that appears to have passed under the frame of the BAFF into Georgiana Slough.

Additional discussion on 3D tracking can be found in **Appendix G**. The 2D and 3D track analyses are valuable in assessing and potentially refining the future BAFF configuration and operations. In addition, these analyses provide a foundation for extrapolating information from the Georgiana Slough tests to develop additional design criteria for BAFF deployments at other locations.



Note: The fish with tag code 2175.28 was undeterred and entered Georgiana Slough. The fish with tag code 2469.26 was deterred and remained in the Sacramento River. The fish with tag code 2721.22 was determined to be eaten downstream (SR) of the BAFF.

Figure 3.2-5 Representative Two-Dimensional Tracks of Chinook Salmon in the Sacramento River



Note: Tag 2868.01 passing below the BAFF frame elevation on April 15, 2012 at 18:12:36 Pacific Daylight Time (BAFF operating). Blue spheres are 1 m diameter tag position estimates from three dimensional track, pink spheres are 1 m diameter elevation estimates from paired hydrophone arrival time measurements. Red spheres and the grey line are the BAFF structure.

Figure 3.2-6 Pathway of a Tagged Chinook Salmon Appearing to Pass under the BAFF Framework into Georgiana Slough

STEELHEAD

The sample sizes for deterrence and protection efficiency when the BAFF was off, when the BAFF was on, and when the BAFF was potentially impaired are summarized in **Tables 3.2-11** and **3.2-12**. In a few instances, a tagged juvenile steelhead appeared to have been eaten and the predator subsequently continued downstream. In these cases, the tags were counted toward overall efficiency but not deterrence or protection efficiency. Therefore, the sample sizes for overall efficiency differ from those for deterrence and protection efficiency when the BAFF was off, when the BAFF was on, and when the BAFF was potentially impaired; the sample sizes for overall efficiency are summarized in **Tables 3.2-13** and **3.2-14**. Of the 299 steelhead that were tagged and released, a total of 264 steelhead passed within 80 m of the BAFF. The number of fish found in these samples ranged from 2 to 14. Based on results of these analyses, subsequent statistical analyses were performed to evaluate BAFF deterrence, protection, and overall efficiency over the range of environmental conditions that occurred during the study period to assess BAFF efficiency as a function of ambient light levels and water velocities passing through the BAFF.

Table 3.2-11
Summary of Tagged Steelhead Deterrence Efficiency and Protection Efficiency Samples Encountering the BAFF during On and Off Operations at Low (< 5.4 Lux) and High (≥ 5.4 Lux) Light Levels

Light Level	BAFF Off (N)	BAFF On (N)	BAFF Potentially Impaired (N)
Low light	15	7	0
High light	16	14	0
Total	31	21	0

Table 3.2-12
Summary of Tagged Steelhead Deterrence Efficiency and Protection Efficiency Samples Encountering the BAFF during On and Off Operations at Low (< 0.25 m/s) and High (≥ 0.25 m/s) Approach Velocities

Approach Velocity Level	BAFF Off (N)	BAFF On (N)	BAFF Potentially Impaired (N)
Low water velocity	15	14	0
High water velocity	16	7	0
Total	31	21	0

Table 3.2-13
Summary of Tagged Steelhead Overall Efficiency Samples Encountering the BAFF during On and Off Operations at Low (< 5.4 Lux) and High (≥ 5.4 Lux) Light Levels

Light Level	BAFF Off (N)	BAFF On (N)	BAFF Potentially Impaired (N)
Low light	17	7	0
High light	17	14	0
Total	34	21	0

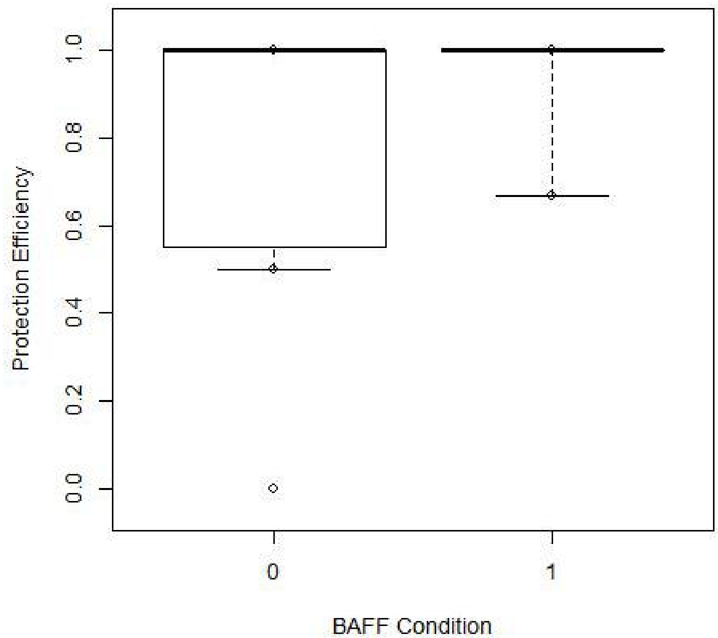
Table 3.2-14 Summary of Tagged Steelhead Overall Efficiency Samples Encountering the BAFF during On and Off Operations at Low (< 0.25 m/s) and High (≥ 0.25 m/s) Approach Velocities			
Approach Velocity Level	**BAFF Off (N)**	**BAFF On (N)**	**BAFF Potentially Impaired (N)**
Low water velocity	16	14	0
High water velocity	18	7	0
Total	34	21	0

The initial statistical testing focused on evaluating the hypotheses that there was no significant difference in deterrence, protection, and overall efficiency of the BAFF when it was on compared to when it was off. As with Chinook salmon, results of initial parametric statistical analysis showed that the basic assumptions of the parametric tests were not met; therefore, the subsequent statistical analyses were based on nonparametric comparisons (i.e., Kruskal-Wallis Tests).

It is important to note that the deterrence efficiency mean when the BAFF was off was 60.2 percent (**Table 3.2-15**). This percentage suggests that the blind classification of deterrence by the Fish Fates Conference teams produced many false positives. In other words, steelhead moved in a fashion that the teams found met the rules for deterrence even when the BAFF was off. The net effect of these false positives was that the percentage point change in deterrence efficiency found in **Tables 3.2-15**, **3.2-16**, and **3.2-17** may be biased low. Furthermore, a tagged fish might be incorrectly determined to be deterred, but the contribution to protection and overall efficiency would remain the same mathematically (see Chapter 2 for equations for deterrence efficiency, protection efficiency, and overall efficiency). Thus, it is possible to have an extremely high protection or overall efficiency value with the BAFF on and a high percentage change in efficiency but a very low value of deterrence efficiency for the same conditions.

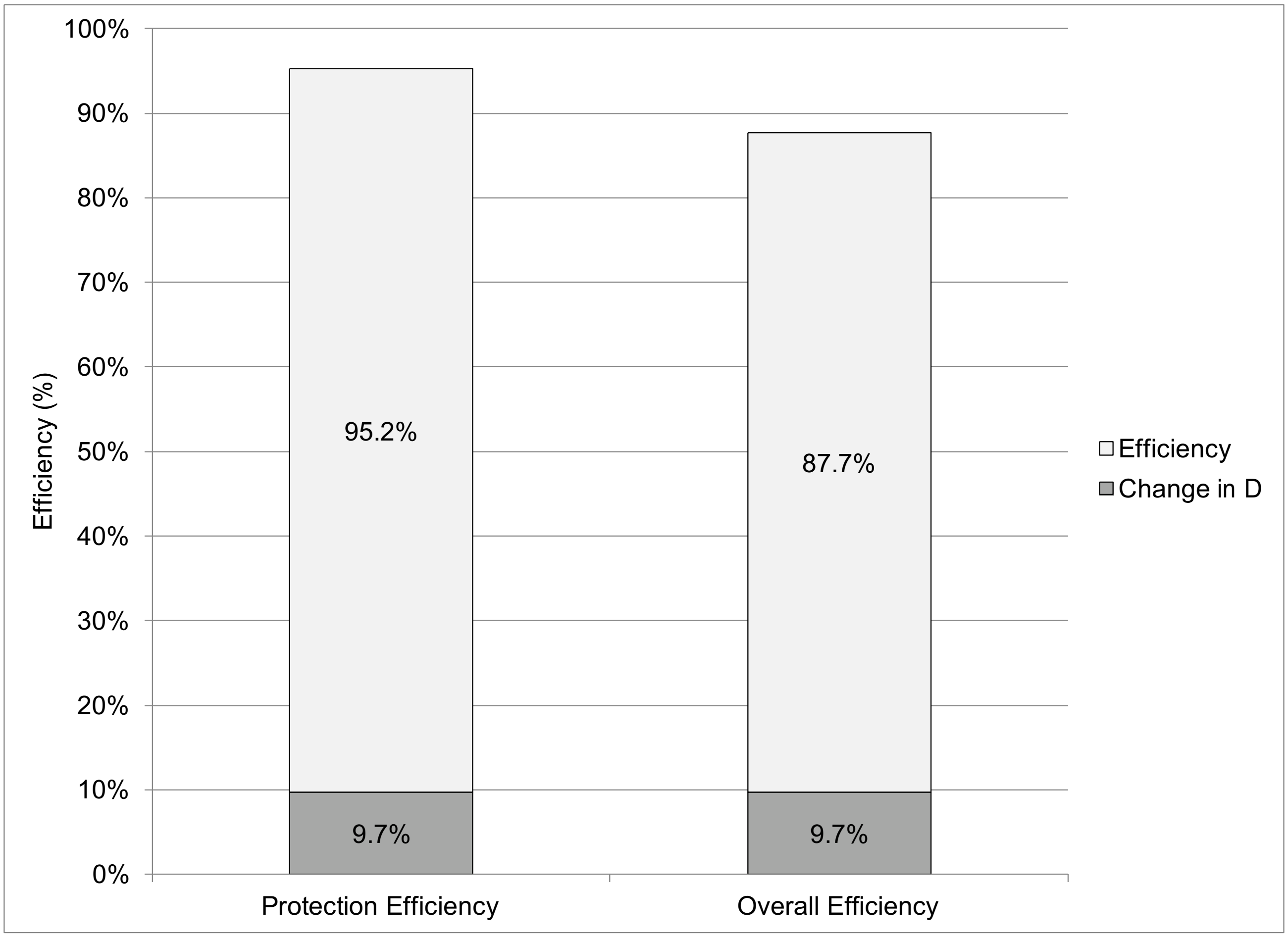
Table 3.2-15 Comparison of BAFF On and Off Operations for Steelhead for Three Steelhead Response Metrics: Deterrence Efficiency, Protection Efficiency, and Overall Efficiency					
Comparison Metrics	**BAFF On Mean**	**BAFF Off Mean**	**Percentage Point Change in Efficiency**	**Kruskal-Wallis X^2**	**P-value**
Deterrence efficiency	0.699	0.602	9.7	2.580	0.1082
Protection efficiency	0.952	0.791	16.1	5.117	0.0237
Overall efficiency	0.877	0.744	13.3	3.379	0.0660

The BAFF On operations resulted in only one statistically significant dependent variable: protection efficiency (**Table 3.2-15**). This suggested that when steelhead were classified as not eaten by predators and passed by the study area when the BAFF was on, there was a statistically higher probability that they would remain in the Sacramento River compared to when the BAFF was off. The distribution of protection efficiency observations when the BAFF was on and off showed a great deal of overlap in range (**Figure 3.2-7**), but the difference between the two samples was still statistically significant (**Table 3.2-15**). Protection and overall efficiency are displayed in **Figure 3.2-8**. However, in **Figure 3.2-8**, the high false positive rate in deterrence classifications likely negatively biased the values of change in deterrence and the magnitude of the bias is unknown.



Note: Observations of potentially impaired BAFF operations were not included. BAFF On is represented as 1, and BAFF Off is represented as 0. The bold line represents the median. The lower line of each box represents the 25th percentile of observations, whereas the upper line represents the 75th percentile. The lower whisker represents the 10th percentile, and the upper whisker represents the 90th percentile.

Figure 3.2-7 Distribution of Steelhead Protection Efficiency during BAFF On and Off Operations



Note: The change in deterrence efficiency (D) is the difference in deterrence efficiency between BAFF On and BAFF Off operations. Observations of BAFF On operations and the BAFF potentially impaired operations are pooled.

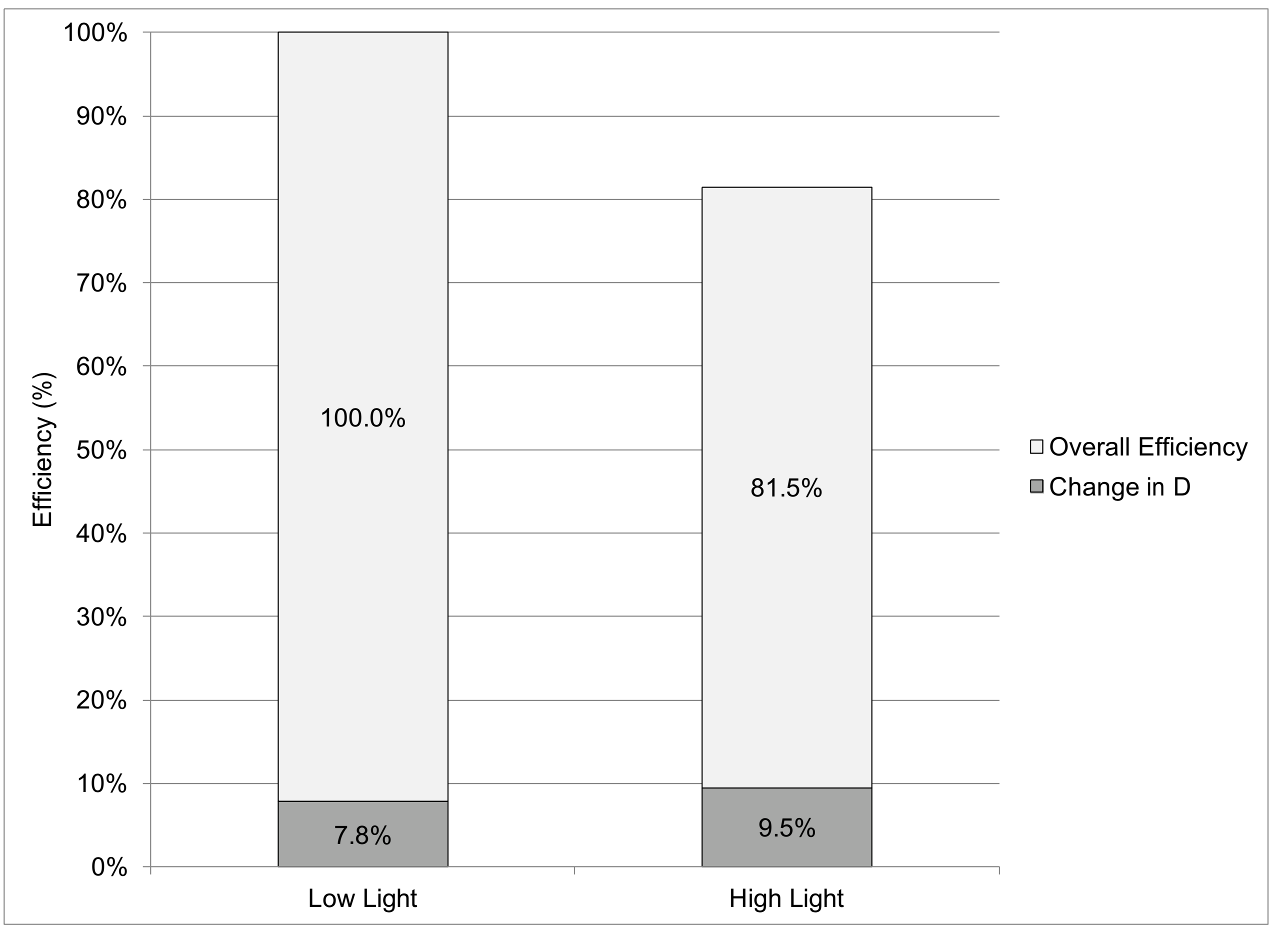
Figure 3.2-8 Relative Contribution of the BAFF Operations to Overall Efficiency for Steelhead

Mean deterrence and overall efficiency were higher when the BAFF was on compared to when it was off (**Table 3.2-15)**. However, both p-values were slightly above the critical alpha level of 0.05. It is possible that the smaller sample sizes (compare **Tables 3.2-1** and **3.2-2** with **Tables 3.2-11**, **3.2-12**, **3.2-13**, and **3.2-14)** may have reduced statistical power to test the steelhead hypothesis compared to the statistical power for testing the same hypothesis for Chinook salmon.

After it was determined that only one dependent variable (protection efficiency) showed barrier performance when the BAFF was off was significantly less than when the BAFF was on, the influence of light on deterrence, protection, and overall efficiency was investigated. Light conditions were divided into two categories: dark (< 5.4 lux) and light (≥ 5.4 lux). Deterrence, protection, and overall efficiency were compared for conditions when the BAFF was off and when the BAFF was on for observations obtained during dark periods. During dark periods, overall efficiency was found to be significantly less when the BAFF was off compared to when it was on (**Table 3.2-16**). Overall efficiency is displayed in **Figure 3.2-9** for the two light levels. Other than the overall efficiency in low light combination, no other dependent variable/light combination was statistically different when the BAFF was off compared to when it was on. This result suggests that steelhead are more sensitive to the BAFF under low light conditions than under high light conditions. It should be noted that the P-value was 0.0587 for the comparison of protection efficiency when the BAFF was off and on during the low light conditions. The small steelhead sample sizes provided lower power than for Chinook salmon, and these two sets of samples might not be distinguished statistically for this reason.

Table 3.2-16
Comparisons of Deterrence, Protection, and Overall Efficiencies for Steelhead during BAFF On and Off Operations under Low (< 5.4 Lux) and High (≥ 5.4 Lux) Light Levels

Comparison Metrics	BAFF On Mean	BAFF Off Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X^2	P-value
Deterrence efficiency—low light	0.657	0.579	7.8	0.572	0.4494
Deterrence efficiency—high light	0.720	0.625	9.5	1.686	0.1942
Protection efficiency—low light	1.000	0.800	20.0	3.573	0.0587
Protection efficiency—high light	0.929	0.782	14.7	2.369	0.1238
Overall efficiency—low light	1.000	0.759	24.1	5.306	0.0213
Overall efficiency—high light	0.815	0.729	8.6	0.625	0.4292



Note: The change in deterrence efficiency (D) is the difference in deterrence efficiency between BAFF On and BAFF Off operations.

Figure 3.2-9 Relative Contribution of the BAFF Operations to Overall Efficiency for Steelhead under Different Light Conditions

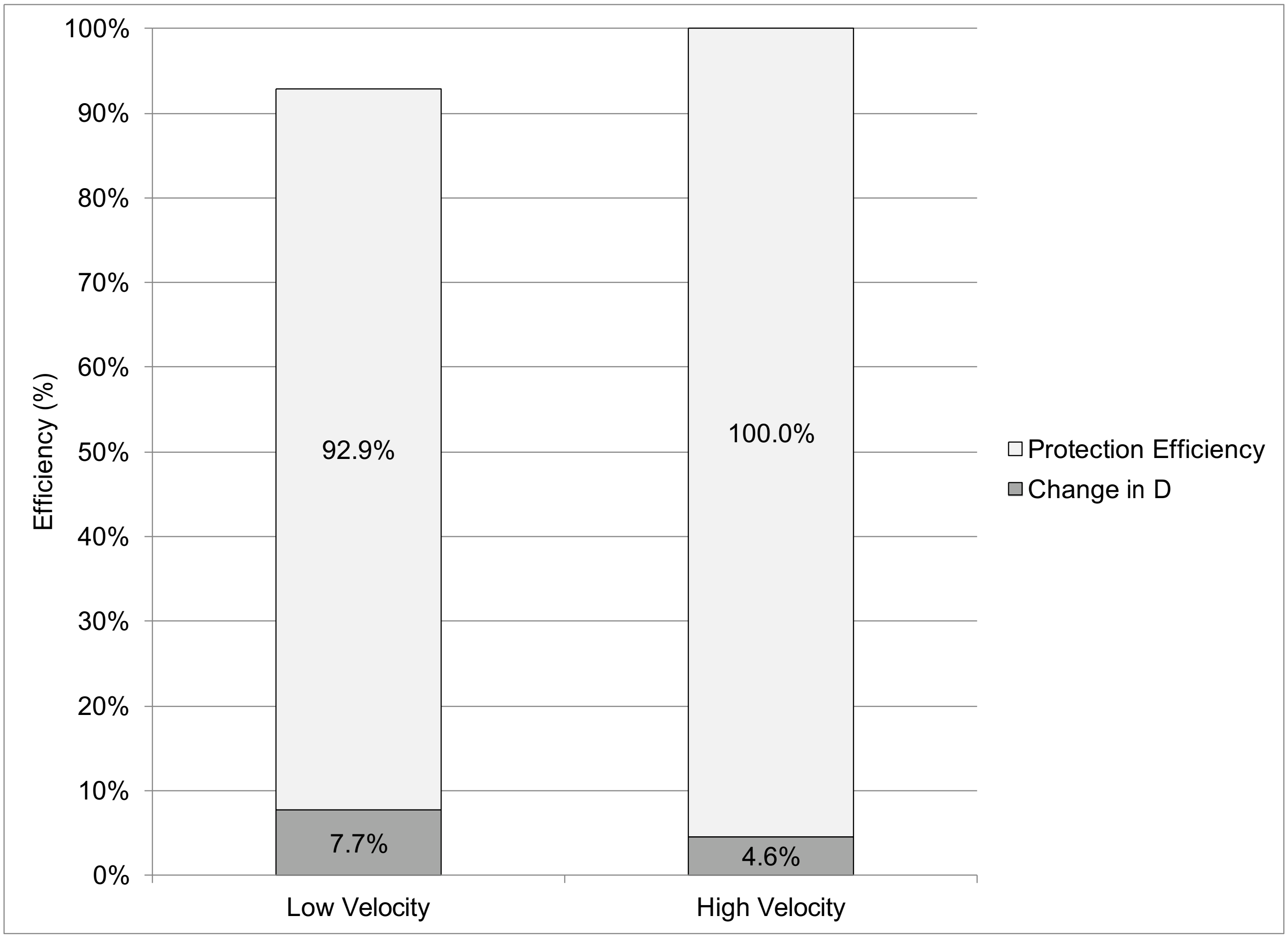
When the approach velocity was < 0.25 m/s, no dependent variable was significantly lower when the BAFF was off compared to when it was on (**Table 3.2-17**). When the approach velocity was ≥ 0.25 m/s, only protection efficiency was significantly lower when the BAFF was off compared to when it was on (**Table 3.2-17**). The mean protection efficiency during high-velocity conditions was 100 percent. The 32.7 percentage point increase in protection efficiency (**Table 3.2-17**) at high velocities suggested that the BAFF warrants further study for its potential to protect steelhead. This result is an example of how the high false positive rate can cause a low value of change in deterrence efficiency while protection efficiency and change in protection efficiency can both be very high.

Table 3.2-17
Comparisons of Steelhead Deterrence, Protection, and Overall Efficiencies for Steelhead during BAFF On and Off Operations under Low (< 0.25 m/s) and High (≥ 0.25 m/s) Approach Velocities

Comparison Metrics	BAFF On Mean	BAFF Off Mean	Percentage Point Change in Efficiency	Kruskal-Wallis X^2	P-value
Deterrence efficiency—low velocity	0.763	0.686	7.7	1.676	0.1954
Deterrence efficiency—high velocity	0.571	0.525	4.6	0.151	0.6979
Protection efficiency—low velocity	0.929	0.917	1.2	0.021	0.8843
Protection efficiency—high velocity	1.000	0.673	32.7	5.792	0.0161
Overall efficiency—low velocity	0.887	0.881	0.6	0.168	0.6821
Overall efficiency—high velocity	0.857	0.622	23.5	2.635	0.1045

When the approach velocity was ≥ 0.25 m/s, protection efficiency was significantly lower when the BAFF was off compared to when it was on (**Table 3.2-17**). For each velocity level, the contribution of the BAFF operations to protection efficiency is displayed in **Figure 3.2-10**. Again, on **Figure 3.2-10**, the high false positive rate in deterrence may have caused negative bias in deterrence by an unknown magnitude.

Visual inspection of the data (**Tables 3.2-15**, **3.2-16**, and **3.2-17)** showed that deterrence, protection, and overall efficiencies were all improved over a wide range of ambient light and water velocity conditions when the BAFF was on compared to when it was off. The statistical significance of these relationships for steelhead proved to be rarer than for Chinook salmon. It could be that there really are fewer significant differences, but a second explanation for fewer statistically significant results was the lowered statistical power resulting from much smaller sample sizes for steelhead compared to Chinook salmon. In addition to the lower power, steelhead exhibited a higher false positive rate in determined deterrence. This higher false positive rate, compared to the false positive rate for Chinook salmon, potentially depresses the percentage point change in deterrence efficiency. These two effects, lower power and high false positive rate, may interact synergistically to produce less statistically significant results for steelhead compared to Chinook salmon because: lower power provides a lessened ability to resolve a true difference between groups, and the high rate of false positives can depress values of deterrence efficiency, the change in deterrence efficiency.

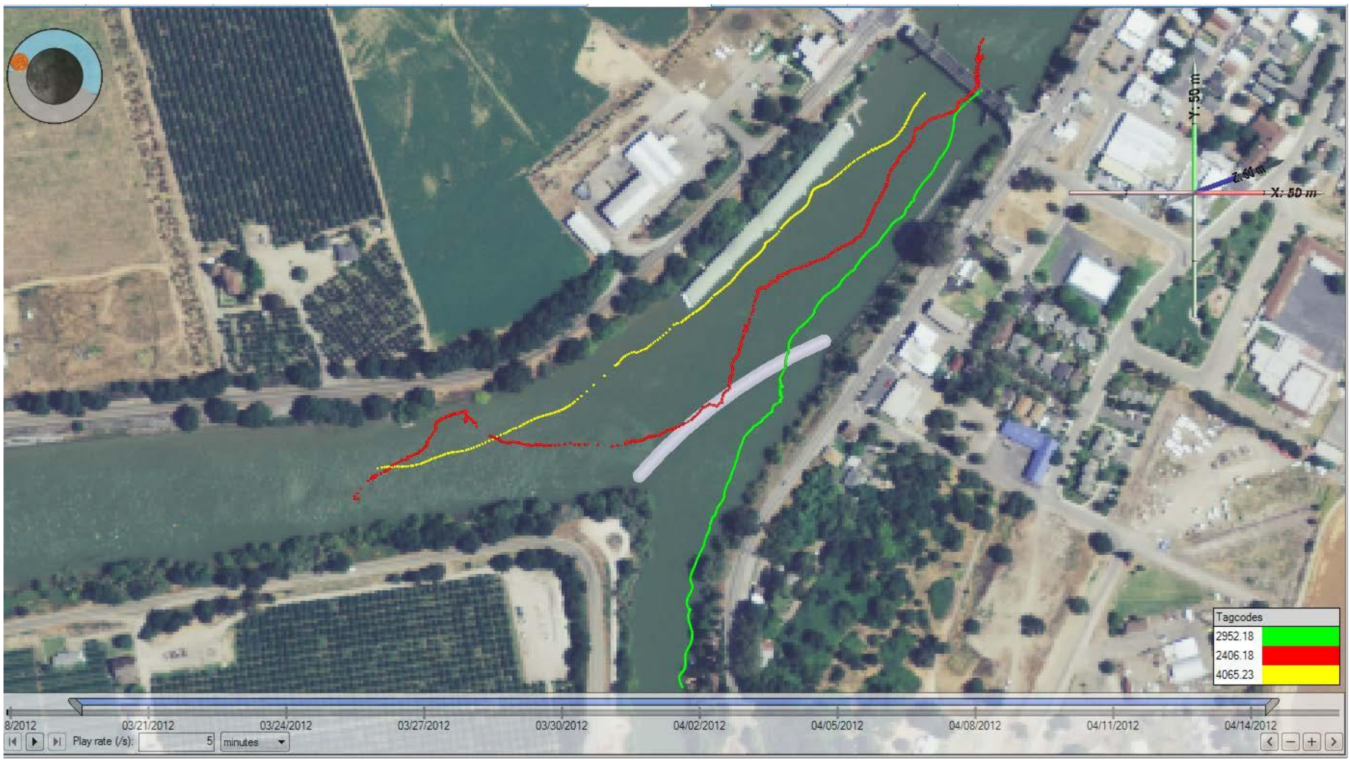


Note: The change in deterrence efficiency (D) is the difference in deterrence efficiency between BAFF On and BAFF Off operations.

Figure 3.2-10 Relative Contribution of the BAFF Operations to Protection Efficiency for Steelhead under Different Velocity Conditions

The effect of the depressed values in deterrence efficiency suggested that the influence of the BAFF is lessened for steelhead compared to Chinook salmon; however, a higher number of samples when the BAFF was on compared to when it was off occurred in three combinations: 1) protection efficiency with all light and velocities combined; 2) overall efficiency at low light; and 3) protection efficiency at high velocities. Thus, it may be concluded that for steelhead, operation of the BAFF significantly improved protection efficiency, especially at high velocities, and overall efficiency in low light. Furthermore, operating the BAFF did deter steelhead, leading to higher protection, but the statistical significance is less demonstrable for steelhead than for Chinook salmon, possibly a result of the smaller sample size. These results suggest that further research with steelhead is warranted.

Two-dimensional tracks were developed for each tagged juvenile steelhead as it migrated downstream in the Sacramento River and encountered the BAFF (**Figure 3.2-11**). These tracks were analyzed by teams at the Fish Fates Conference, where classifications of predation on tagged salmonids, or lack thereof, and deterrence were made. The deterrence and predation classifications and the 2D tracks provided a basis for examining individual fish responses to the BAFF as a function of water velocity and distance from the BAFF.



Note: The fish with tag code 2952.18 was undeterred and entered Georgiana Slough. The fish with tag code 2406.18 was deterred and remained in the Sacramento River. The fish with tag code 2952.18 was determined to be undeterred because it made no movement away from the BAFF.

Figure 3.2-11 Representative Two-Dimensional Tracks of Steelhead in the Sacramento River

SUMMARY COMPARISON OF BAFF PERFORMANCE BETWEEN CHINOOK SALMON AND STEELHEAD

Deterrence efficiency when the BAFF was on was significantly greater for juvenile steelhead (69.9 percent) than for juvenile Chinook salmon (56.1 percent); however, the change in deterrence between BAFF On and BAFF Off for steelhead was relatively small, suggesting that the BAFF operations were not solely responsible for the greater deterrence efficiency results for steelhead. No statistically significant difference was detected in either protection or overall efficiency between juvenile Chinook salmon and steelhead when the BAFF was on, suggesting that operation of the BAFF provided relatively consistent protection and overall efficiency for both species.

Under low light levels (<5.4 lux) when the BAFF was on, deterrence efficiency was less for juvenile Chinook salmon (49.2 percent) when compared to steelhead (65.7 percent). Protection efficiency when the BAFF was on was also less for Chinook salmon (84.2 percent) when compared to steelhead (100 percent). Overall efficiency when the BAFF was on was found to be greater for steelhead (100 percent) than for Chinook salmon (84.2 percent). The same pattern in differences was observed between steelhead and Chinook salmon under high light levels (≥5.4 lux) for deterrence and protection efficiency, with the exception of overall efficiency for steelhead (81.5 percent) that was less than for Chinook salmon (95.0 percent), suggesting that steelhead may be more sensitive to the BAFF under low light conditions than under high light conditions.

Under low approach velocity levels (<0.25 m/s) when the BAFF was on, deterrence efficiency was less for juvenile Chinook salmon (57.3 percent) when compared to steelhead (76.3 percent). Protection efficiency when the BAFF was on was slightly higher for Chinook salmon (94.5 percent) when compared to steelhead

(92.9 percent). Overall efficiency when the BAFF was on was found to be greater for Chinook salmon (94.2 percent) than for steelhead (88.7 percent). Under high approach velocity levels (≥0.25 m/s) when the BAFF was on, deterrence, protection, and overall efficiency were higher for steelhead (57.1 percent, 100 percent, and 85.7 percent, respectively) than for Chinook salmon (48.5 percent, 51.5 percent, and 59.1 percent, respectively). Yearling steelhead were larger than juvenile Chinook salmon used in these tests and likely had better swimming capability, and it is hypothesized that this increased swimming ability potentially contributed to the greater response of steelhead to the BAFF.

SUMMARY COMPARISON OF BAFF PERFORMANCE BETWEEN 2011 AND 2012 FOR JUVENILE CHINOOK SALMON

Results of a comparison of 2011 and 2012 juvenile Chinook salmon data found no statistically significant differences in deterrence efficiency, protection efficiency, or overall efficiency when the BAFF was on between the two years. The deterrence efficiency when the BAFF was on was 56.1 percent in 2012 and 50.4 percent in 2011. Protection efficiency when the BAFF was on was 89.0 percent in 2012 and 90.5 percent in 2011. Overall efficiency when the BAFF was on was 89.7 percent in 2012 and 90.8 percent in 2011. Similarly, no significant differences were detected in deterrence, protection, or overall efficiency when the BAFF was on under low and high light levels or during low and high water velocities between 2011 and 2012. These results suggest that despite the large differences in Sacramento River flows during the 2011 and 2012 surveys, operation of the BAFF provided consistent protection and overall efficiency in reducing the risk of juvenile Chinook salmon entrainment into Georgiana Slough.

SUMMARY COMPARISON OF BAFF PERFORMANCE UNDER DIFFERENCE COVARIATES

Additional statistical analyses were conducted that factored in different covariates (i.e., fish length, water temperature, turbidity, and discharge) to determine if these variables were important factors in 2012 BAFF performance.

Fish Lengths

Results showed that over the range of fish size (measured by FLs) did not significantly influence whether Chinook salmon or steelhead would be deterred, enter Georgiana Slough, or continue down the Sacramento River when the BAFF was on or off.

There was a highly significant difference between FLs of Chinook salmon and steelhead ($P < 0.0001$) used in the 2012 study. However, within species, there were no significant differences in FLs for deterred versus undeterred, protected versus unprotected, or for fish that exited the Sacramento River versus Georgiana Slough when the BAFF was on or off. A small range of sizes was used for both species (Chinook: mean 138 mm range 104-215 mm; steelhead: mean 215 mm, range 119-258 mm). This small range of sizes likely limited our ability to test for the influence of fish size on BAFF operations.

Water Temperature

When the BAFF was off, deterrence efficiency for Chinook salmon increased slightly with increasing temperatures; however, this increase was not statistically significant. When the BAFF was on, deterrence efficiency increased from Group 1 (< 12.9°C) to Group 2 (12.9 to 15.0°C) and again increased from Group 2 to

Group 3 (> 15^{o}C); however, these increases also were not statistically significant. There was a trend for increasing deterrence efficiency with increasing temperature and this suggests that future research in this area might shed more light on this relationship. Myrick and Cech (2001) reported the optimal temperature for growth for Chinook salmon and steelhead to be 15 to 19^{o}C. Thus, 15^{o}C was used for the upper break and the lower break.

When the BAFF was off, deterrence efficiency for steelhead did not increase with temperature; however, when the BAFF was on, deterrence efficiency showed an increase (50.3 percent) from low temperatures to high temperatures (15^{o}C was selected as the threshold between high and low). These results suggested that with increasing temperature into the optimal temperature range (15 to 19^{o}C; Myrick and Cech 2001), steelhead swimming performance may have increased the ability for steelhead to swim away from the BAFF which would have caused an increase in deterrence efficiency.

Turbidity

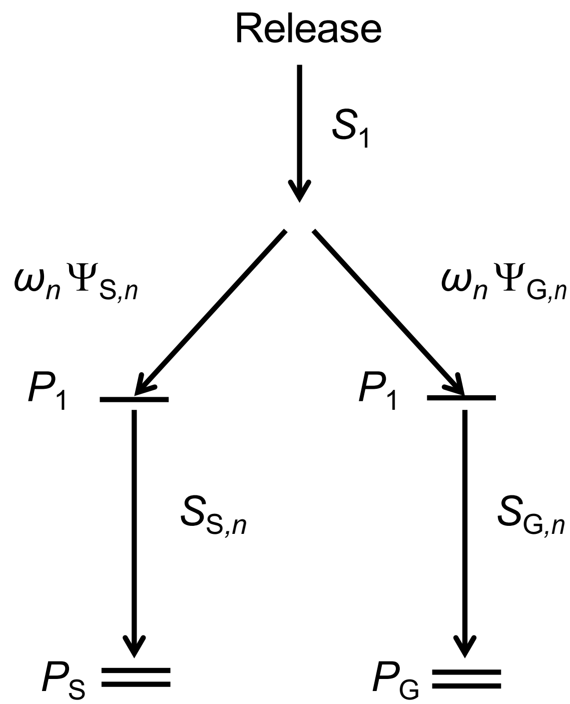
Results showed that when the BAFF was off, deterrence efficiency for Chinook salmon decreased significantly as turbidity increased. It is hypothesized that this phenomenon might have occurred because turbidities were strongly correlated with discharge (Spearman's $r = 0.831$, $P < 0.0001$). When lower discharges occurred, there tended to be lower turbidities and lower velocities. When the BAFF was off, deterrence efficiency for steelhead also decreased significantly with increasing turbidities. The mechanism for this relationship was likely the same as that for Chinook salmon. Overall, during the combined times when the BAFF was on and off, turbidity showed no statistically significant effect on overall efficiency for Chinook salmon or steelhead.

3.3 SURVIVAL AND ROUTE ENTRAINMENT PROBABILITY ANALYSIS

3.3.1 METHODS

A mark-recapture survival model was developed using telemetry stations at three locations: 1) the divergence of the Sacramento River and Georgiana Slough (study array); 2) downstream of the BAFF in the Sacramento River (peripheral hydrophone site); and 3) downstream of the BAFF in Georgiana Slough (peripheral hydrophone site) (**Figure 3.3-1**). The model, which was constructed using the methods of Perry et al. (2010), estimated three sets of parameters: survival (S_{hi}), detection (P_i), and route entrainment probabilities (Ψ_h) (**Table 3.3-1**).

Survival probabilities were estimated to identify the probability that a fish would survive while moving from location i to location i+1 within each route (h). Detection probabilities were estimated to identify the probability that a tag would be detected at a given location; detection assumes that the tagged fish has survived with an operational transmitter. Route entrainment probabilities were estimated to identify the probability that a fish would enter route h: in this case, the Sacramento River (route "S") or Georgiana Slough (route "G"). In addition, survival and route entrainment probabilities were estimated for BAFF On and BAFF Off treatments. This required that an additional parameter, ω_n, be included in the model. This parameter is used to estimate the probability that fish would arrive at the river junction during BAFF On (ω_{on}) and BAFF Off (ω_{off}) treatment periods.



Note: A horizontal bars represents a telemetry location, and two horizontal bars represent the peripheral hydrophones.

Figure 3.3-1 **Mark-Recapture Model Schematic Used to Estimate Survival, Detection, and Route Entrainment Probabilities**

Table 3.3-1
Parameter Definitions for the Mark-Recapture Model

Parameter	Definition
S_1	Survival from release to array
$S_{S,n}$	Survival from array to Sacramento River peripheral hydrophones
$S_{G,n}$	Survival from array to Georgiana Slough peripheral hydrophones
P_1	Detection probability of the array
P_S	Overall detection probability of the peripheral hydrophones in the Sacramento River
P_G	Overall detection probability of the peripheral hydrophones in Georgiana Slough
ω_{on}	Probability of arriving at the array with the BAFF On
$\Psi_{S,n}$	Probability of entering the Sacramento River conditional on BAFF status
$\Psi_{G,n}$	Probability of entering Georgiana Slough conditional on BAFF status

Note: The subscript “n” denotes parameters estimated separately for BAFF On and BAFF Off.

The data for the model are composed of observed counts of detection histories that define whether fish were detected at the array and/or peripheral hydrophones, the route of detection, and the BAFF treatment at the time fish were detected near the BAFF (**Table 3.3-2**). Each detection history has three detection codes. The first code indicates that fish were released upstream of the BAFF; this code is "1" for all fish released for the study. The second code indicates that fish were not detected in the array ("0"), that fish entered the Sacramento River ("*S*"), or that fish entered Georgiana Slough ("*G*"). It also indicates the BAFF operation when fish were detected ("on," "off"). Fish were assigned a route based on the final disposition of 2D tracks as determined at the Fish Fates Conference. The third code indicates whether fish were detected at peripheral hydrophones downstream of the BAFF in the Sacramento River ("*S*") or in Georgiana Slough ("*G*") or at neither site ("*0*"). A fish that arrived in the array when the BAFF was on, exited the array via the Sacramento River, and was detected at downstream peripheral hydrophone exit site, for example, was coded as "1 *Son* S." A fish that entered the array when the BAFF was off and entered Georgiana Slough but was not detected at the downstream peripheral hydrophone was coded as "1 *Goff* 0" (**Table 3.3-2**).

Table 3.3-2
Detection History Frequencies Used in the Mark-Recapture Model to Estimate Survival, Detection, and Route-Entrainment Probabilities for Late Fall-Run Chinook Released in Spring 2012

Model	Detection History Overall	Frequency
Overall model	*1 0 0*	326
	1 0 S	0
	1 0 G	0
	1 Soff 0	30
	1 Soff S	413
	1 Son 0	37
	1 Son S	481
	1 Goff 0	24
	1 Goff G	119
	1 Gon 0	9
	1 Gon G	60
Sacramento double-array model	*S1 0*	13
	0 S2	18
	S1 S2	863
Georgiana Slough double-array model	*G1 0*	6
	0 G2	2
	G1 G2	171

Fish classified as having been eaten in the array needed to be assigned to one of the three reaches (i.e., from the release site to the array or from the array to one of the downstream detection sites). Fish classified as having been eaten upstream of the BAFF were assigned to the upstream reach by coding them as "1 0 0." Fish classified as having been eaten downstream of the BAFF were coded as "1 *Son* 0," "1 *Soff* 0," "1 *Gon* 0," or "1 *Goff* 0," depending on the migration route and BAFF operation. Fish eaten upstream of the BAFF were incorporated into the estimate of S_1, whereas fish eaten downstream of the BAFF were incorporated into the estimate of either S_S or S_G.

Detection probabilities at the downstream detection sites (P_S and P_G) were estimated by using detection data provided by two peripheral hydrophones installed at each monitoring location. A mark-recapture model for peripheral hydrophones, described as double arrays by Skalski et al. (2002), allowed the study team to estimate both the detection probability for each detection location separately and the overall detection probability of both peripheral hydrophone locations. Detection histories for the peripheral hydrophone locations are composed of two codes that indicate whether fish were detected at only one detection location, only the other detection location, or both detection locations (e.g., "G1 0," "0 G2," or "G1 G2") (**Table 3.3-2**).

Model parameters were estimated to the maximum likelihood using optimization routines in the software program USER (Lady et al. 2008). The standard error and profile likelihood 95 percent CIs were estimated for each parameter. Stations that had perfect detection histories were not estimable and were assigned a value of 1. Reduced models were fit that set parameters equal between BAFF On and BAFF Off to test whether Ψ_G, S_S, and S_G differed between treatments. These hypotheses were assessed using likelihood ratio tests.

In addition to fish released explicitly for the study, fish released by the SRCSD were also analyzed as they moved through the study area. Fish moved through the study area when the BAFF was on, off, in the process of being removed, and after it was completely removed. This presented the opportunity to examine route entrainment when the BAFF was on, off, and when it was no longer in place. This portion of the analysis is presented in **Appendix H**.

3.3.2 Results

Two alterations were made to classifications from the Fish Fates Conference. First, fish that were classified as "Predation Unknown" at the Fish Fates Conference were assumed to have been live tagged salmonids, and their classification was changed to "Not Eaten." Second, the BAFF operation status of "Potentially Impaired" was changed to "On." In addition, fish that were in the study area when operation of the BAFF was changed were eliminated from the analyses. For this analysis, a total of 1,499 late fall-run Chinook salmon and 296 steelhead were used to estimate survival and route entrainment probabilities (**Tables 3.3.-2** and **3.3-3**).

For late fall-run Chinook salmon, survival from release to the array was relatively low (0.783 percent) (**Table 3.3-6**). Survival estimates from the 3D array to the downstream nodes of each channel were higher than for the upstream reach but still lower than the corresponding survival estimates from the 2011 study (Perry et al. 2012). Survival from the exit of the 3D array to the downstream Sacramento River nodes ($S_{S,n}$) differed little when the BAFF was on and off ($X^2 = 0.051$, $P = 0.822$) (**Table 3.3-6**). Likewise, survival from the exit of the array to the downstream Georgiana Slough nodes ($S_{G,n}$) differed little when the BAFF was on and off ($X^2 = 0.508$, $P = 0.476$) (**Table 3.3-6**). For both BAFF treatments, survival downstream of the array was higher in the Sacramento River than in Georgiana Slough, but this difference was significant only when the BAFF was off (for BAFF On: $X^2 = 2.54$, $P = 0.111$; for BAFF Off: $X^2 = 11.49$, $P < 0.001$).

Table 3.3-3
Detection History Frequencies Used in the Mark-Recapture Model to Estimate Survival, Detection, and Route-Entrainment Probabilities for Steelhead Released in Spring 2012

Model	Detection History Overall	Frequency
Overall model	*1 0 0*	100
	1 0 S	0
	1 0 G	0
	1 Soff 0	5
	1 Soff S	76
	1 Son 0	9
	1 Son S	67
	1 Goff 0	6
	1 Goff G	23
	1 Gon 0	2
	1 Gon G	8
Sacramento double-array model	*S1 0*	4
	0 S2	3
	S1 S2	136
Georgiana Slough double-array model	*G1 0*	1
	0 G2	0
	G1 G2	30

Table 3.3-4
Estimates of Detection Probabilities and Standard Errors for All Telemetry Stations for Acoustically Monitored Late Fall-Run Chinook Salmon Released in Spring 2012

Station	Detection Probability	Standard Error
P_1	1.000	NA
P_S	1.000	<0.001
P_{S1}	0.980	0.005
P_{S2}	0.985	0.004
P_G	1.000	<0.001
P_{G1}	0.988	0.008
P_{G2}	0.966	0.014

Notes: P_S and P_G are the overall detection probabilities calculated from estimates of each detection location detection probability (P_{S1}, P_{S2} and P_{G1}, P_{G2}, respectively). "NA" for the standard error indicates that the detection probability was set to 1.0 because all fish were detected.

Table 3.3-5
Estimates of Detection Probabilities and Standard Errors for All Telemetry Stations for Acoustically Monitored Steelhead Released in Spring 2012

Station	Detection Probability	Standard Error
P_1	1.000	NA
P_S	0.999	<0.001
P_{S1}	0.978	0.012
P_{S2}	0.971	0.014
P_G	1.000	NA
P_{G1}	1.000	NA
P_{G2}	0.968	0.032

Notes: P_S and P_G are the overall detection probabilities calculated from estimates of each detection location detection probability (P_{S1}, P_{S2} and P_{G1}, P_{G2}, respectively). “NA” for the standard error indicates that the detection probability was set to 1.0 because all fish were detected.

Table 3.3-6
Survival and Route Entrainment Probabilities for BAFF On/Off Operations for Late Fall-Run Chinook Salmon Released in Spring 2012

BAFF Operation	Reach/Route	Survival Probability ($S_{h,n}$)		Route Entrainment Probability ($\Psi_{h,n}$)	
		Estimate (SE)	95% CI	Estimate (SE)	95% CI
NA	Release to array	0.783 (0.011)	0.761, 0.803	NA	NA
On	Sacramento River	0.929 (0.011)	0.905, 0.949	0.882 (0.013)	0.855, 0.907
Off		0.933 (0.012)	0.907, 0.954	0.756 (0.018)	0.720, 0.790
On	Georgiana Slough	0.870 (0.041)	0.777, 0.935	0.118 (0.013)	0.093, 0.145
Off		0.832 (0.031)	0.766, 0.888	0.244 (0.018)	0.210, 0.280

Notes: Survival was estimated from the release site to the array and from the start line of the array to peripheral hydrophones located in either the Sacramento River or Georgiana Slough. Confidence intervals (CIs) were estimated with profile likelihood methods. SE = standard error.

Survival estimates for steelhead showed a pattern similar to that for late fall-run Chinook salmon. Survival from release to the 3D array was low (0.662) (**Table 3.3-7**). Survival from the exit of the 3D array to the downstream Sacramento River nodes ($S_{S,n}$) differed little when the BAFF was on and off (X^2 = 1.57, P = 0.211) (**Table 3.3-7**). Likewise, survival from the exit of the array to the downstream Georgiana Slough nodes ($S_{G,n}$) differed little when the BAFF was on and off (X^2 = 0.002, P = 0.964) (**Table 3.3-7**). For both BAFF treatments, survival downstream of the 3D array was higher in the Sacramento River than in Georgiana Slough, but this difference was significant only when the BAFF was off (for BAFF On: X^2 = 0.477, P = 0.490; for BAFF Off: X^2 = 4.45, P = 0.035).

Table 3.3-7 Survival and Route Entrainment Probabilities for BAFF On/Off Operations for Steelhead Released in Spring 2012					
BAFF Operation	Reach/Route	Survival Probability ($S_{h,n}$)		Route Entrainment Probability ($\Psi_{h,n}$)	
		Estimate (SE)	95% CI	Estimate (SE)	95% CI
NA	Release to array	0.662 (0.027)	0.607, 0.714	NA	NA
On	Sacramento River	0.882 (0.037)	0.797, 0.942	0.884 (0.035)	0.805, 0.94
Off		0.939 (0.027)	0.873, 0.978	0.736 (0.042)	0.649, 0.813
On	Georgiana Slough	0.800 (0.126)	0.501, 0.964	0.116 (0.035)	0.060, 0.195
Off		0.793 (0.075)	0.624, 0.912	0.264 (0.042)	0.187, 0.351

Notes: Survival was estimated from the release site to the array and from the start line of the array to peripheral hydrophones located in either the Sacramento River or Georgiana Slough. Confidence intervals (CIs) were estimated with profile likelihood methods.
SE = standard error.

3.3.3 DISCUSSION

As in the 2011 study, the study team found strong evidence in 2012 that operation of the BAFF influenced route entrainment. With the BAFF On, a significantly lower fraction of both late fall-run Chinook salmon and steelhead entered Georgiana Slough. For both species, entrainment into Georgiana Slough when the BAFF was on was about 50 percent lower than entrainment when the BAFF was off.

Survival from release to the array was lower for late fall-run Chinook salmon when compared to the results of previous studies. In 2011, survival from release to the array was 0.957, over 17 percentage points higher than observed in 2012 (S_1 = 0.783). Although lower survival might have been expected because lower flows were observed in 2012, considerably higher survival during similarly low flows was observed in previous studies. Over four years, estimates of survival for this reach have ranged from 0.88 to 0.99 (Perry 2010; Perry et al. 2012).

Three potential hypotheses could explain these observations. First, because fish were released into this reach, tagging- and handling-related mortality may have contributed to lower survival relative to survival observed in other studies where fish were released further upriver (acclimation effects). However, this is not believed to have been an issue based on the results of the fish tagging effects study showing that no fish died (see **Appendix D**). Second, the previous studies were conducted from December through February, whereas this study was conducted from February through March; therefore, seasonal differences in predation pressure (predator abundance and temperature-related metabolic requirements) could have led to differences in survival. Last, lower flows and river velocities could have made more difficult the classification of fish as having been eaten, leading to false-positive classification of predation events. For example, of the 1,499 late fall-run Chinook salmon used in the analyses, 55 never arrived in the study area, and 270 were classified as being consumed by predators upstream of the BAFF based on 2D tracks that exhibited predator-like behavior. Future comparison of results from predator detection algorithms to predator classifications from the Fish Fates Conference should provide insight about the accuracy of the low survival estimates observed for the reach upstream of the array.

3.4 HYDRODYNAMICS AND CRITICAL STREAKLINE ANALYSIS

The analysis of water velocity patterns and juvenile salmon entrainment in Georgiana Slough discussed in the following sections builds on analysis of juvenile salmon entrainment in the DCC and Georgiana Slough during the 2001 and 2003 DCC studies. The USGS analysis of the DCC studies resulted in the Entrainment Zone Conceptual Model (EZCM) of juvenile salmon entrainment (Blake and Horn 2003, 2006), which is a conceptual framework for understanding juvenile salmon entrainment rates in junctions as the product of a two-step process. The first step in this process occurs in the river upstream of the junction; as outmigrating salmon respond to the physical environment they encounter, the interaction between their behavior and water velocities will determine their location in the river cross-section when they enter the distributary area. When effects of these individual behavioral/physical interactions are aggregated for outmigrants approaching a distributary under similar conditions the result is repeatable spatial distributions of outmigrant densities in the river cross-section immediately upstream of the distributary.

The second step controlling juvenile entrainment rates occurs at the scale of the distributary, where the time needed for the fish spatial distribution to significantly evolve is longer than the typical junction transit time. At this point, water velocity patterns within the junction will largely determine the percentage of fish in each portion of the river cross section that will enter each branch of the junction. Areas of a junction with similar entrainment rates can be grouped into entrainment zones, and the overall entrainment in a junction branch can be approximated by multiplying each zone's entrainment rate by the number of outmigrants in the entrainment zone. The two-step separation inherent to the EZCM is possible because fish spatial distributions typically evolve at timescales that are much longer than the transit time in junctions under hydrodynamic conditions typical in the Delta, except during short-lived slack water periods.

Conceptualizing juvenile salmon entrainment as the result of a two-step process makes it easier to understand the effects of covariates that control entrainment, because physical and biological process that effect entrainment can be separated into two distinct groups based on whether they influence the spatial distribution of salmon entering the junction, or whether they influence the location of entrainment zones within the junction.

- **Upstream, or Lagrangian processes:**

  The interaction of upstream channel bottom topography, structures (such as docks, bridge piers, etc.), water velocity patterns that vary with river inputs and tidal forcings and outmigration behavior as fish move through the river (i.e., in a Lagrangian frame) determine when and where in the cross-section fish enter the junction, and as a result, determine how many fish are exposed to a given temporal evolution of the entrainment zones in a junction over a given period of time.

- **Near-field, or Eulerian processes:**

  In the immediate vicinity of the junction a combination of water velocity patterns and fish behavior determine how many fish go into each junction branch. When the water velocity is high relative to fish swimming capability, entrainment is primarily governed by physical process. Behavior tends to dominate entrainment when the velocities are low, typically during short-lived slack water periods. Entrainment zones are governed by a combination of the local bathymetry in the junction, particularly the difference in capacities between channels, and vary temporally with river flows and the tides.

In summary, the foundation of the EZCM is the idea that physical processes tend to govern entrainment zones at any point in time, but overall entrainment rates for a junction over a period of time are a result of upstream processes which determine the entrance distributions and arrival timing of fish in the junction coupled with the temporal evolution of entrainment zones within junctions.

While water velocities can be used to predict the locations of entrainment zones within a junction, the location and size of each branch's entrainment zone cannot be used to predict entrainment probabilities unless it is known how many fish actually use a given portion of the river (i.e., the spatial distribution of fish within the junction is also known). For example, if fish were uniformly distributed throughout the river cross-section then entrainment probabilities at a junction, in the absence of a fish barrier, could be calculated based on water velocity and flow data alone. However, data from the 2001 and 2003 DCC studies (Blake and Horn 2003, 2006), the 2006 Clarksburg Bend Study (USGS, unpublished data), and the 2011 GSNPB Study (DWR 2012) all show that study fish are not uniformly distributed in river junctions and river bends. As a result, there is a need to combine knowledge of the water velocity patterns in a river junction with knowledge of the spatial distribution of fish within the junction in order to understand and predict entrainment rates. To this end, the following sections are focused on:

1. Developing analytical methods that encapsulate information about the near-field water velocity patterns in the junction into time series that can be used to predict the zone of entrainment for each channel in a junction at a given moment in time;
2. Measuring the distribution of tagged fish in the Georgiana Slough junction for a variety of entrainment zone patterns and BAFF operations; and
3. Combining understanding of the near-field water velocity patterns, our estimates of entrainment zone locations, and our knowledge of the spatial distribution of fish to develop a mechanistic understanding of entrainment at junctions in general and, specifically, the BAFF's influence on entrainment rates in the Georgiana Slough junction.

3.4.1 CRITICAL STREAKLINE DEVELOPMENT

Evidence from past studies on juvenile Chinook salmon entrainment into Georgiana Slough suggests that instantaneous water velocity patterns in the immediate vicinity of the Georgiana Slough divergence affect entrainment into Georgiana Slough (Horn and Blake 2004; DWR 2012). While it would be ideal to directly measure water velocity patterns within the junction at high spatial and temporal resolution over the range of conditions that outmigrating salmon are likely to encounter during winter and spring months, the costs associated with measuring a junction-scale velocity field on a continuous basis make this approach impractical. Instead, side-looking Horizontal Acoustic Doppler Current Profilers (H-ADCPs) were used to make numerous velocity measurements in the junction area, and a novel interpolation scheme was used to interpolate the surface water velocity fields in the junction at 15-minute intervals for a subset of the 2012 GSNPB Study period (**Appendix F**). These velocity field estimates were analyzed in conjunction with GPS tracks recorded by drifters released by the USGS and DWR during the 2012 GSNPB Study (**Appendix F**) with the goal of developing techniques that would allow researchers to estimate the location of entrainment zones within tidally forced junctions without measuring the full 2D velocity field. The first metric developed to estimate the location of entrainment zones in the Georgiana Slough junction is the critical streakline calculation.

Particles (or drifters) that enter the junction of the Sacramento River with Georgiana Slough are either transported into Georgiana Slough or continue down the Sacramento River (see **Figure 3.4-1**). The location of split between the entrainment zones, defined as the critical streakline, is the point in the river cross-section where the two entrainment zones meet.

The critical streakline concept is a way of collapsing a complex flow field into its essence with regard to fish fates, providing a simple metric for comparing the potential for entrainment under a variety of conditions within a junction and between junctions. For example, at any instant in time the critical streakline reduces the complexity of the entire flow field down to a single Lagrangian trajectory that can be well represented by the distance from the shore (see *Xu* on **Figure 3.4-1**), to the trajectory's location in the river cross-section. The advantages and limitations of various techniques for computing the location of the critical streakline are discussed in detail in **Appendix F**, but in general, critical streakline calculations are most informative if researchers have detailed velocity measurements, drifter tracks, or fish entrainment data to use for the calculation. In the absence of this type of detailed, junction-specific data, the location of the critical streakline can be estimated using flow station discharge records to compute junction discharge ratios which can then be scaled by the cross-sectional width of the river to produce critical streakline location estimates (see Perry et al. 2012). Detailed analysis of critical streakline estimates produced using this approach suggests that, in the absence of detailed junction information, it is preferable to use the junction discharge ratios as a direct surrogate for entrainment zone location, rather than scaling these ratios to produce low precision estimates of the critical streakline location (see **Appendix F** for additional discussion). For this reason, discharge ratios provide a better general metric for understanding the effects of tidally forced velocity patterns on juvenile salmon entrainment in junctions, because discharge ratios can be computed accurately for all junctions in the Delta using existing flow station data.

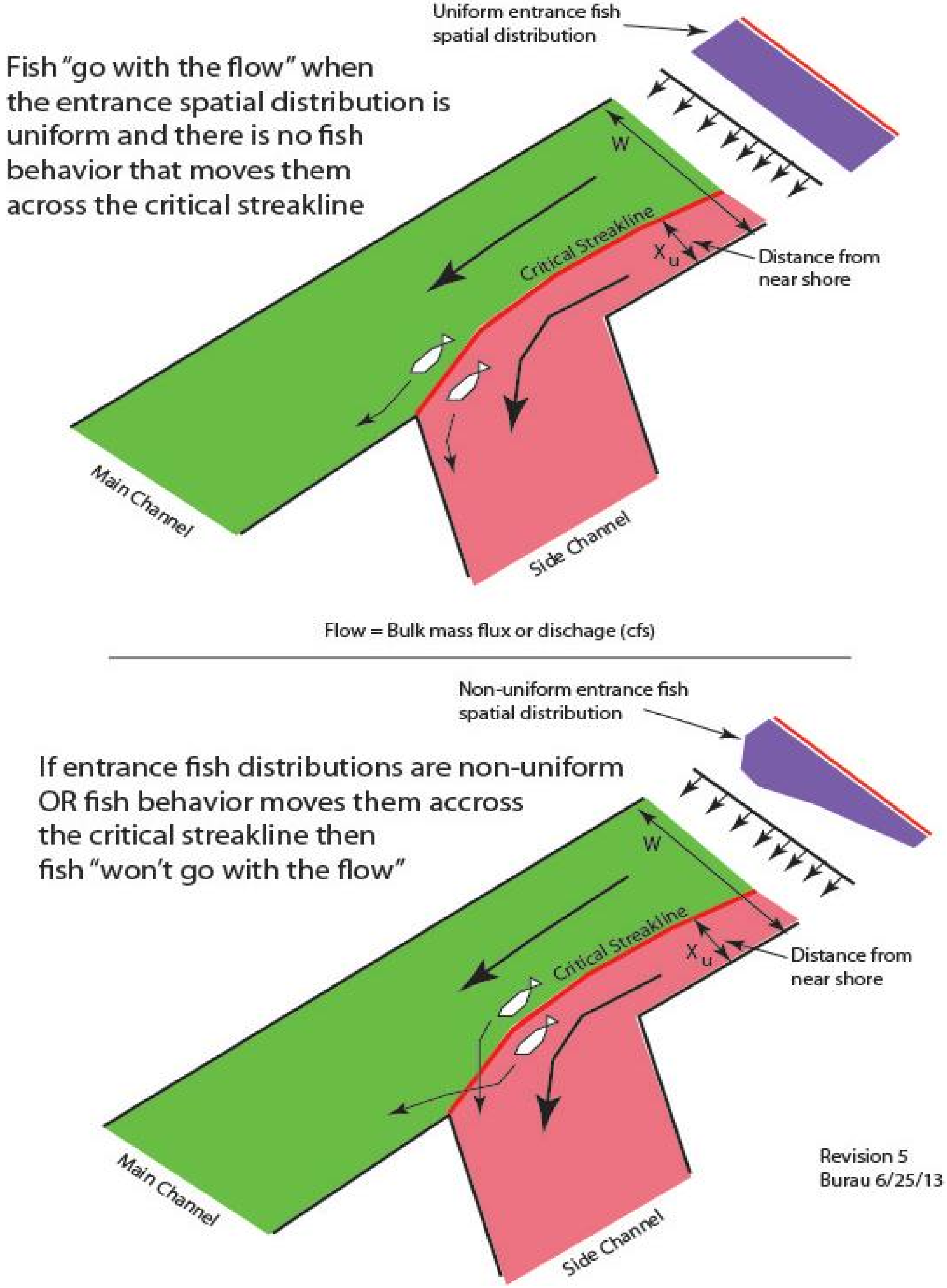
DISCHARGE RATIO

The streakline position is extremely useful because one can quantify the degree to which physical processes contribute to entrainment by comparing streakline positions with observed tagged fish spatial distributions. However, streakline positions are site-specific and depend on the local bathymetry, and in the absence of detailed bathymetry and velocity data they collapse to the discharge ratio scaled by the width of the channel (**Appendix F**). Thus, if the discharge ratio R_U is defined as the proportion of the flow that enters the side channel from the main channel from upstream and R_D is defined as the proportion of the flow that enters the side channel from downstream, the equation can be shown as:

$$X_u = W_u \left(\frac{Q_s}{Q_u}\right) = W_u R_u$$

and

$$X_d = -W_d \left(\frac{Q_s}{Q_d}\right) = W_d R_d$$



Source: USGS

Note: Red regions denote the entrainment zone for the side channel whereas the green regions show the region where fish continue along the main channel. The red line between these regions is the critical streakline. Top panel shows the required conditions for fish to "go with the flow" – in this case the bulk discharge in each channel. These conditions include a uniform entrance fish spatial distribution and behaviors that don't result in fish crossing the critical streakline. In the bottom panel are indicated those conditions that create conditions where fish aren't distributed in proportion to the flows in each channel. These conditions include a non-uniform entrance fish distribution as is shown and behaviors that cause fish to transit the critical streakline.

Figure 3.4.1 Conceptual Diagram of Critical Streakline and Entrainment in a Junction

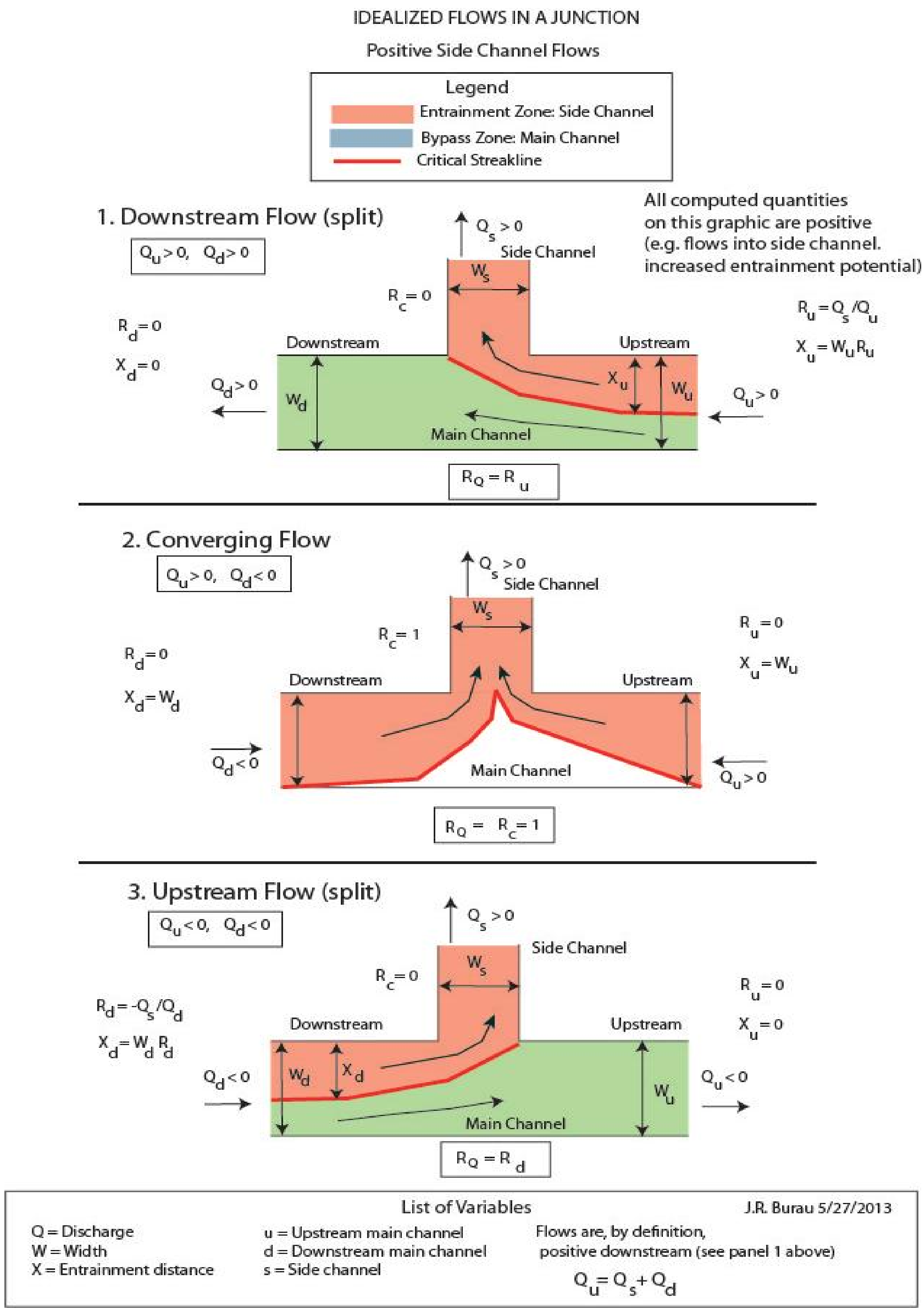
Many tidally forced junctions in the Delta experience a third set of velocity conditions where the flow converges into the side channel from both upstream and downstream. To account for these time periods, discharge ratios are defined under converging flow conditions as R_C, which is identically 1 (or 100 percent). Defining the discharge ratios in this way suggests a series of six states shown in **Figures 3.4-2a** and **3.4-2b** that represent all of the conditions that must be considered to correctly compute the discharge ratio in junctions where the tidal currents are reversing. Since each of the states are mutually exclusive, the total discharge ratio can be defined as:

$$R_Q = R_U + R_C + R_D$$

which varies from zero to unity and encompasses all possible flow conditions. Conceptually, R_Q represents the fraction of the total flow entering the junction that enters the side channel of interest, and by extension, R_Q provides a general idea of the size of the side channel's entrainment zone relative to the junction.

If R_Q is close to 0, the channel's entrainment zone is small and entrainment risk is low; if R_Q is close to 1, the channel's entrainment zone covers most of the junction area and that entrainment risk will be close to 100 percent. During times when R_Q varies between these extremes, the location of a side channel's entrainment zone relative to the spatial distribution of fish in the junction will determine overall entrainment risk. By convention, the component R's are all strictly positive for water entering a side channel, and negative for water exiting a side channel into the main channel. In this way, conditions where fish may be entrained in a side channel but return when the flows reverse in the side channel into the main channel.

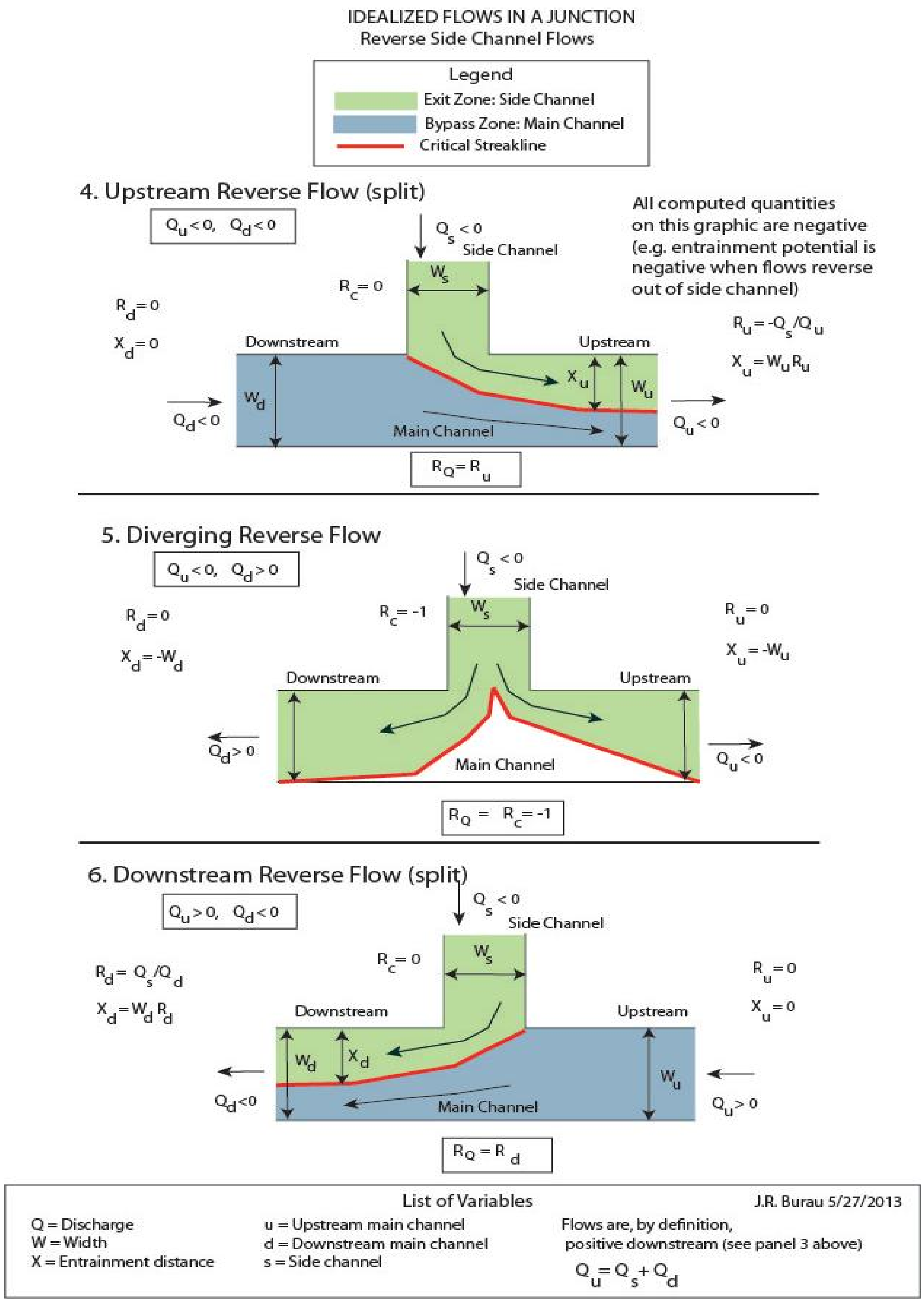
By maintaining all three of these variables separate from the total discharge ratio (R_Q), each of the conditions that varies throughout the tidal cycle can be independently quantified, which is important in understanding what types of fish guidance technologies may work in a given junction. In addition, the total discharge ratio can help to explain how each of the flow conditions contributes to the tidally averaged discharge ratio under a variety of hydrologic conditions, especially when the flows from the side channel are reversing.



Source: USGS

Notes: 1) downstream flow in the main channel; 2) converging flow; and 3) upstream flow.

Figure 3.4-2a **Three Flow Conditions in a Tidally Forced Junction Where the Water is Entering a Side Channel**



Source: USGS

Notes: 4) downstream flow in the main channel; 5) converging flow; and 6) upstream flow.

Figure 3.4-2b **Three Flow Conditions in a Tidally Forced Junction Where the Water is Exiting a Side Channel**

Variation in the Discharge Ratios at the Tidal Timescale

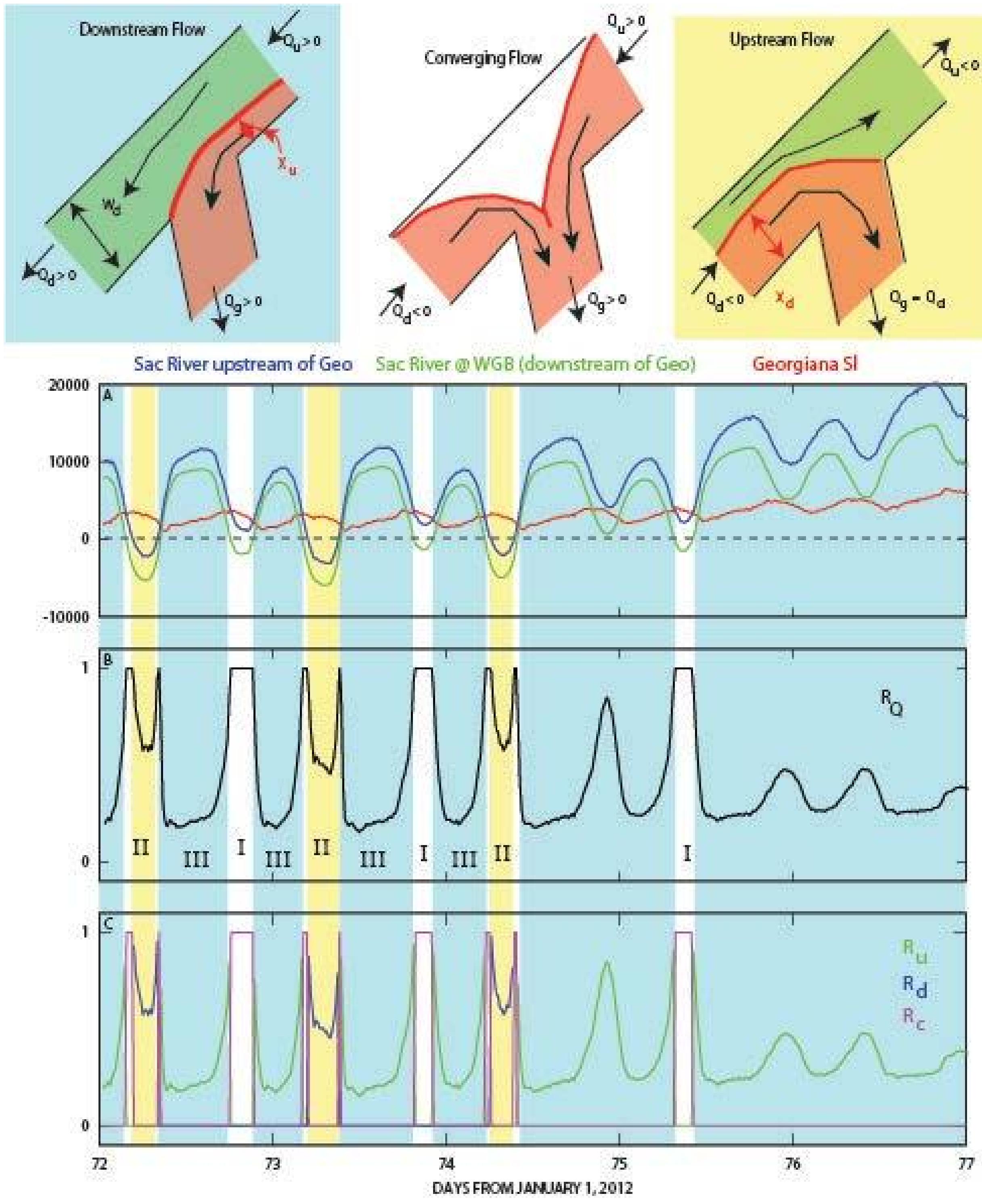
Figure 3.4-3 plots the three-component discharge ratios and the shaded periods correspond to each of the three flow states shown in the diagrams at the top of the figure: light blue = periods that are indicative of downstream flow; white (no shading) - periods of converging flow; and, yellow = periods of upstream flow.

These figures show that at low Sacramento River flows downstream flow conditions occur most often in Georgiana Slough, the next most frequent are periods of upstream flow, and lastly, converging flow conditions occur with the lowest frequency.

Tidal periods that encompass converging flows have two basic modes, as illustrated in frames I and II in **Figure 3.4-3**. Periods of extended converging flow occur when the flow reverses into Georgiana but the tides do not have the momentum to reverse the flow upstream in the Sacramento River above Georgiana Slough, as is indicated by I. Periods of converging flow are extremely important for overall entrainment of fish in a side channel because these periods represent periods of weak to no bypass flows in the main channel; during these periods all of the water from the main channel enters the side channel. It is likely that during these conditions, the majority of the fish entering the junction will also enter the side channel, unless they find velocity refugia along the bank opposite the side channel or behind structures. These converging conditions often occur during spring tides when a substantial diurnal inequality exists. In these cases converging flows occur almost every other flood tide. During the maximum flood tide, the periods of converging flow are short lived, and occur for short periods of time immediately before and after the flood tide flows on the Sacramento River bypass Georgiana Slough (**Figure 3.4-3,** B, II).

During the downstream and upstream flow periods the discharge ratio varies, significantly in the case of the downstream flow condition. In a prismatic channel, the discharge ratio can be thought of as the percentage of the width of the channel that is used to convey water into the side channel. Therefore, the progression for the upstream and downstream conditions both start with $R_Q = 1$ during converging flow conditions, then as either condition progresses and less of the channel width is involved in providing water to the side channel, the remainder of the water and the fish in it bypasses the side channel. In the case of the prolonged downstream condition, the discharge ratio decreases from 100 percent to less than 25 percent of the channel width (see, for example, III in **Figure 3.4-3**, C), whereas during the peak upstream flow conditions 50 percent to 60 percent of the channel width is involved (see, for example, II in **Figure 3.4-3,** C). At Sacramento River discharges of 15,000-30,000 cubic feet per second (cfs) (Julian Days 75.5-77), the percentage of the Sacramento River channel involved in providing water to Georgiana Slough is relatively low, in the range of 25-50 percent. This is due to the fact that the Georgiana Slough cross-section is considerably smaller than the Sacramento River cross-section at this location, so most of the flow continues seaward in the Sacramento River.

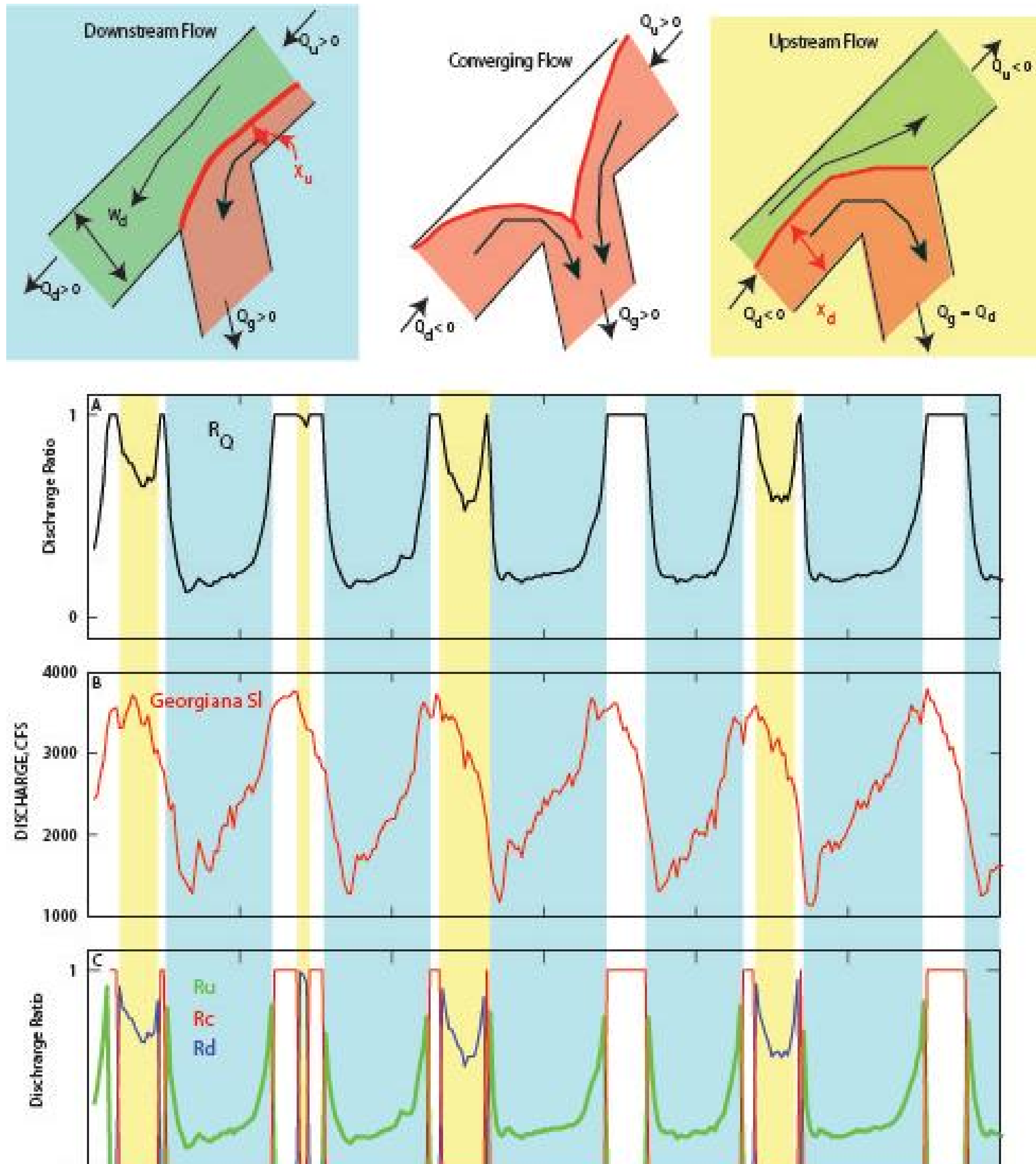
Figure 3.4-4 shows that both the converging and upstream flow conditions occur on the descending limb of flows that enter Georgiana Slough, but both conditions begin near the peak of the tidal discharge into Georgiana Slough. Therefore, both converging and upstream conditions occur when significant volumes of water, and potentially fish, are entering Georgiana Slough. It is therefore likely that both of these conditions contribute significantly to the tidally averaged entrainment of fish into Georgiana Slough.



Source: USGS

Notes: Time series plots of (A) the discharge in the Sacramento River upstream of Georgiana Slough (blue), the Sacramento River downstream of Georgiana Slough (green), and Georgiana Slough (red), (B) the total tidal discharge ratio R, and (C) the component discharge ratios RU (flow entering Georgiana Slough from upstream, green), RD (flow entering Georgiana Slough from downstream, blue) and RC (converging flow into Georgiana Slough) during a transition from bi-directional flow to uni-directional flow as the Sacramento River's tidally average discharge increased in 2012. The upper portion of the diagram gives the color coding for the various flow states (light blue for downstream flow, white for converging flow and yellow for reversing flow. During reversing conditions it is clear the flows in the junction cycle through all three of the flow states. In particular the switch between states on either side of converging flow conditions can be quite rapid – condition II above.

Figure 3.4-3 Time-Series Plots of Three-Component Discharge Ratios



Source: USGS

Notes: Time series plots of (A) the total discharge ratio, R, (B) the discharge in Georgiana Slough, and (C) the component discharge ratios RU (flow entering Georgiana Slough from upstream, green), RD (flow entering Georgiana Slough from downstream, blue) and RC (converging flow into Georgiana Slough) during low Sacramento River flow period.

Figure 3.4-4 Time-Series Plots of Converging and Upstream Flow Conditions

3.5 SPATIAL ANALYSIS OF FISH DISTRIBUTION AND BEHAVIOR

This section is focused on quantifying the spatial distribution of acoustically tagged juvenile salmon in the Georgiana Slough junction under a variety of hydrodynamic conditions, and on investigating the relationships between the spatial distribution of acoustically tagged salmon in the junction, the water velocity patterns in the junction, the installation and operation of the BAFF, and the entrainment of study fish into Georgiana Slough. Given this focus, the analyses in this section are mostly limited to analyzing the near-field processes that were directly observed in the study area, although the analysis of arrival time distributions provides insights into the effects that upstream processes have on the timing of outmigrant fish movements.

3.5.1 METHODS

In order to understand the effects of water velocity patterns on entrainment of juvenile salmon in Georgiana Slough, knowledge of the water velocity patterns must be combined with estimates of the spatial distribution of juvenile salmon in the divergence area. Given a set of acoustic tag tracks one can calculate the 2D empirical probability distribution for tracked fish using numeric methods, but a large number of tracks must be used to create 2D probability distribution functions (PDFs) that are representative of the spatial distribution of fish in the junction for a given set of conditions. This need for a large sample size presents complexities in analyzing the data collected at the Georgiana Slough junction, because the tidally influenced velocity patterns in the junction evolve continuously with the tides and changes in Sacramento River flow rates. For this reason, if one estimates the spatial distribution of a large group of fish tracks that entered the junction over a contiguous block of time (e.g., all of the fish that passed through the junction in a 24-hour period), that distribution cannot be used to understand the effects of a particular water velocity pattern on route selection because it will represent the distribution of fish exposed to a range of velocity patterns. Instead, fish tracks must be aggregated into covariate groups based on the conditions fish were exposed to when they entered the junction, so that the empirical 2D PDFs can be calculated for each covariate group in order to provide a valid estimate of the spatial distribution of fish in the junction area for the conditions of interest.

Because it is impractical to release the number of fish required to calculate representative empirical PDFs for every distinct set of measured covariate values at the junction of the Sacramento River and Georgiana Slough, fish tracks need to be aggregated into groups that are exposed to a range of similar covariate values. The critical streakline and flow ratio metrics developed in earlier sections (see Section 3.4) are crucial to this process, because these metrics collapse the complexities of the 2D velocity fields in the junctions into time series that can be used to sort fish into groups that experienced similar velocity conditions. Time series of other covariates, such as light conditions and BAFF operations can be combined with the time series representing velocity conditions in order to further separate fish into specific covariate groups that can be used to examine junction entrainment as a function of multiple covariates. Empirical 2D PDFs can be calculated for each covariate group to estimate the spatial distribution of fish in the junction for specific covariate conditions, and statistics calculated from these PDFs can be used to gain insights into the mechanisms affecting juvenile salmon entrainment in Georgiana Slough.

DATA SOURCES AND RELEASE GROUPS

Because spatial analyses are conducted on groups of fish aggregated based on covariate values rather than temporal continuity, fish tracks from multiple release groups and different studies can be combined for aggregation as long as all of the covariates needed for aggregation were measured in a similar manner across all studies. In general, the increased sample sizes that result from combining tracks from multiple studies and release groups improve the spatial resolution and statistical power of the 2D statistics that are calculated for each group, and using data collected over multiple years helps reduce the influence of unmeasured covariates by increasing the range of environmental conditions fish experienced during data collection.

For this analysis, tracks from tagged juvenile Chinook salmon released during the 2008 North Delta Study and the 2011 and 2012 GSNPB studies were combined for aggregation. Because Sacramento River flows were unusually high during the 2011 GSNPB Study, combining data from both years allowed us to evaluate the performance of the BAFF across a wider range of river conditions than would be possible if the data sets were analyzed individually. Additionally, integrating the data from the 2008 study provides valuable information on fish distributions during low flow periods that were not captured during the GSNPB studies, and for higher flow periods, it allowed us to investigate the effects of the barrier structure by making comparisons between fish tracks collected when the barrier was installed but not operated, and data from the 2008 study when no barrier was present. Tracks from acoustically tagged steelhead that passed through the array, and tracks from acoustically tagged juvenile Chinook salmon released by the SRCSD study were analyzed separately. In order to focus this analysis on the mechanics of entrainment of juvenile Chinook salmon, tracks from fish that were classified as eaten during the Fish Fates Conference were removed from the pool of 2012 GSNPB Study tracks prior to covariate aggregation.

TIMING OF COVARIATE ASSIGNMENT

The goal of the covariate aggregation process was to separate tracks into groups that could be used to develop estimates of the spatial distribution of fish passing through the junction under a narrow range of specific velocity conditions. In order to achieve this goal, it was important to classify each fish track based on the values of the covariates of interest at the time when the fish's fate was "decided" within the junction. It is not hard to meet this requirement when classifying tracks that moved through the junction quickly during times when covariates were changing slowly. However, one consequence of the tidal forcing at the Georgiana Slough junction is that during some tidal conditions fish can spend a relatively long time in the junction area when velocity patterns are changing rapidly, because some portions of the junction area experience slack water conditions when other areas are transitioning to reversing and converging flow conditions. As a result, fish tracks were assigned covariate values to be used during aggregation based on the velocity conditions, light values, and barrier operations at the time when they were closest to the cumulative distribution function point (CDF point). The CDF point was chosen so that this approach would yield the best results for all tracks, and is located slightly inside Georgiana Slough because this is the only area in the junction that does not experience slack water conditions at low flows. The flows in Georgiana Slough almost never reverse – only occurring over a couple of hours in the roughly 10 years of discharge measurements made by the USGS.

COVARIATE SIGNALS USED FOR AGGREGATION

Tracks from acoustically tagged juvenile Chinook salmon were separated into covariate groups for aggregation based on three covariate signals:

- Barrier operations: the barrier operation from the 2011 and 2012 GSNPB studies were used to create a continuous barrier operations time series ranging from 0 to 3. A barrier operations value of zero indicated that the barrier was installed but turned off, a value of 0.5 indicated that only one component (e.g., light, sound, or bubble curtain) of the barrier was operating, a value of 1.0 indicated that the barrier was fully operating, and a value of 3.0 indicated that the barrier was not installed. Tracks from all three studies were assigned a barrier operations value using linear interpolation to determine the value of the barrier operations signal at the time when the track was closest to the CDF point. Tracks with a barrier operations value greater than 0.0 and less than 1.0 were discarded, as these fish were in the immediate vicinity of the barrier when operations were being changed, or when the barrier was partially damaged or operating incorrectly;

- Light: down-welling radiation data from the Sacramento International Airport meteorological monitoring station was used to estimate the light conditions in the junction at the time when each fish track was closest to the CDF point using linear interpolation; and

- Velocity conditions: A time series that could be used to aggregate tracks based on junction velocity conditions was computed by calculating junction upstream and downstream flow ratios using USGS 15-minute gauge data as described in Section 3.2, and then these flow ratios were scaled to create two critical streakline time series that could be used to estimate the velocity patterns each fish experienced in the junction. Linear interpolation was used to find the junction critical streakline value at the time each fish track was closest to the CDF point. The scaling process used to convert the flow ratios into the critical streakline time series is discussed in the following section. For the purpose of this analysis, the term 'downstream critical streakline value' refers to the location of the critical streakline in the river cross-section above the junction when flow is moving in the downstream direction on ebb tides. The term 'upstream critical streakline value' refers to the location of the critical streakline in the river cross-section southwest of the river junction when the flow is moving in the upstream direction on flood or converging tides.

SPATIAL APPORTIONMENT

After covariate values were assigned to each fish track or track segment, software written by the USGS was used to extract spatial statistics from the group of tracks. This process was performed in two steps: First, spatial apportionment was carried out to assign the unique tag code and covariate values associated with each fish track to a discretized representation of the junction area. Second, covariate aggregation software written by the USGS was used to extract spatial statistics from the apportioned data for each covariate aggregate group. The spatial apportionment step was carried out as follows:

- Bathymetric data was used to generate a 5-m-x-5-m 2D grid of discrete cells within the junction area. Cells boundaries were aligned parallel to the UTM grid Easting and Northing axes. Bathymetry data was used to classify each grid cell as dry (outside of the river banks), or wet (inside of the river banks). A 5-m grid size was chosen so that grid cells would be large enough to contain enough fish to compute entrainment rates for each covariate group, while maintaining enough grid cells in the junction area to resolve spatial gradients in two dimensional statistics;

- Linear interpolation was used to estimate a position at one second intervals for each fish track to ensure that at least one position would fall within each of the grid cells that the track passed through;

- Each interpolated position from every track was assigned to a grid cell, and the tag code and covariate information for the track was entered into a binary data structure for the grid cell. If that tag code had already passed through that grid cell, its information was not entered a second time, so that each grid cell was limited to containing one record for each tag code in order to avoid autocorrelation errors and double counting errors. This limitation also reduced the bias introduced by resident predators and holding fish, because a fish that spent hours in the array could only be counted once in each grid cell;

- Each interpolated point was assigned to a separate structure that kept track of the total amount of time each tag code spent in each cell. This information can be used to estimate residence time for covariate groups; and
- The process was repeated for all tracks and track segments, and the results were stored in a spatially explicit binary data structure that was used for the covariate aggregation. For the juvenile Chinook salmon analysis, 5,323 individual tracks and track segments were apportioned within the Georgiana Slough junction area.

COVARIATE AGGREGATION

After the spatial apportionment was completed, 2D statistics were extracted for each covariate aggregate group so that these statistics could be used to estimate the distribution of parameters for fish that passed through the junction under specific water velocity, light, and barrier conditions. This process was carried out as follows:

- Cumulative distribution functions (CDF) were used to determine the upstream and downstream critical streakline values and down-welling light values associated with each covariate group;
- These values were entered into software written by the USGS to extract covariate statistics from the binary data structure created during spatial apportionment. This software calculated the total number of unique tag codes in each grid cell that have covariate values falling within the range of covariate time-series values chosen for each covariate group. These tag codes were further separated by barrier condition (Off, On, out), and by fate (Sacramento River downstream (ds), Sacramento River upstream (us), and Georgiana Slough (gs);
- The software output a .csv file defining the number of fish with each fate for every grid cell in the domain. Separate .csvs were created for each fate for all combinations of water velocity, barrier operation, and light covariate groups; and
- These output files were loaded into the MATLAB® (The MathWorks, Inc.) data processing environment, and scripts written by the USGS were used to compute a variety of spatial statistics.

Water velocity covariate groups used for the juvenile salmon spatial analysis (see **Table 3.5-1**) were chosen to balance the following competing requirements:

- A significant number of water velocity covariate groups are needed to avoid grouping fish tracks that experienced dissimilar water velocity conditions into the same aggregate group;
- A large number of tracks is needed in each water velocity covariate group to allow the tracks assigned to each group to be further broken down by light and barrier operations;
- The boundaries between covariate groups should be chosen to so that differences between each group are physically significant; and

- The boundaries between covariate groups should be chosen so that covariate groups have similar sample sizes.

Due to both the high flows during the 2011 GSNPB Study period and the fact that almost all of 2012 GSNPB tracks that entered the junction during non-ebb conditions were classified as eaten, almost all of the tracks from the 2011 and 2012 GSNPB studies used for the spatial analysis were in the Ebb2, Ebb3, and Ebb 4 periods. Consequently, the effects of the barrier can only be analyzed for this narrow range of ebb-tide velocity conditions.

Table 3.5-1
Water Velocity Covariate Boundaries

Covariate Group Name	Lower Critical Streakline Boundary*	Upper Critical Streakline Boundary*	Velocity Pattern/Tidal Condition Represented
Ebb1	DS -37.5	DS -5	Ebb tide when most water is bypassing Georgiana Slough
Ebb2	DS -5	DS 0.0	Ebb tide when the critical streakline is over the BAFF and sweeping velocities are likely to be highest.
Ebb3	DS 0.0	DS +10	Ebb tide when the critical streakline is slightly to the right of the BAFF looking downstream.
Ebb4	DS +10	DS +40	Ebb tide when the critical streakline is significantly to the right of the BAFF and the angle between the BAFF and water velocities is large
Ebb5	DS +40	DS +107.5	Ebb tide when most of the water in the junction is entering Georgiana Slough
Converging Flow	DS +107.5 US 100	DS +107.5 US 100	Converging flow when water is entering Georgiana Slough from the Sacramento River above and below the junction
Weak Flood	US 0.0	US +62.5	Weak flood tide. During weak flood tides water on the left hand side of the Sacramento River (looking downstream) downstream of the junction reverses before water on the right hand side of the river in this area.
Strong Flood	US +62.5	US 100	Strong flood tide
Slack	Transition values	Transition values	Slack water and transition conditions on either side of converging flow and reversing flow conditions. During these conditions swim numbers (movement) are high and juvenile salmon are capable of sustained movement in all directions.

Note:
* DS = Downstream critical streakline time series value, which applies to flow moving downstream during ebb tide conditions.

Fish tracks associated with each water velocity covariate group were further classified into light and dark groups based on down-welling light time series values. Cumulative distribution functions showing the distribution of fish between each water velocity covariate after fish were separated into light and dark condition groups. Crepuscular and fully light conditions were grouped together because there were not enough fish tracks in each water velocity covariate group to produce spatial statistics for crepuscular time periods.

The number of fish tracks in each of the other release groups was not large enough to support significant covariate aggregation, so the analysis of these tracks was limited.

METRICS USED FOR SPATIAL ANALYSIS

Empirical density distributions were produced during the spatial apportionment and covariate aggregation process. These density distributions were used to compute the spatial distribution of a variety of metrics useful for understanding entrainment at the Georgiana Slough divergence. The spatial distribution of these metrics was estimated by computing the metric of interest for the set of fish that passed over each 5m x 5m grid cell in the junction domain, and the resulting 2D distribution of these metric values was interpolated onto a 1m x 1m grid to improve visualization of spatial gradients. Density distribution metrics used for the spatial analysis were:

- Empirical Fish Density Distribution – 2D representation of the spatial distribution of fish in the junction for an aggregate group showing the number of fish in each grid cell for the aggregate group. The empirical fish density distribution can be expressed in terms of total number of fish, or percent of total mass;
- Total Number of Fish - The empirical fish density distribution expressed as the total number of fish in each grid cell for the aggregate group;
- Total Mass - The empirical fish density distribution expressed as the total number of fish in each grid cell normalized by the total number of fish in the aggregate group and multiplied by 100 percent. Total mass indicates the percent of fish that pass through each grid cell for a given aggregate group. The two dimensional distribution of total mass is the spatial empirical probability distribution function for fish mass during the aggregate period. Total mass is used instead of total number of fish when comparisons are made between aggregate groups in order to account for sample size differences between aggregate groups;
- Entrainment Rate - The fraction of the total fish in each grid cell entering Georgiana Slough. Ranges from 0.0 to 1.0;
- Entrainment Percentage - The entrainment rate multiplied by 100 percent to express entrainment as the percent of the total fish in each grid cell entering Georgiana Slough. The entrainment percentage is used for visualization purposes when bounded values produce better results;
- Entrainment - The number of fish that enter Georgiana Slough in each grid cell. Entrainment is expressed as a percent of the total number of fish that passed through the junction for each aggregate group in order to account for sample size differences between aggregate groups. Entrainment is the product of a grid cell's entrainment rate multiplied by a grid cell's total mass; and
- Reduction in Entrainment - The reduction in the entrainment in a grid cell between one aggregate group and another (for example BAFF On and BAFF Off). The reduction is expressed as the difference in the entrainment values for each grid cell between aggregate groups, and is in the same units as entrainment (The number of fish entering Georgiana Slough divided by the total number of fish in each aggregate group). For example, a reduction in entrainment value of 5 indicates that entrainment in Georgiana Slough decreased by 5 percent of the total number of fish that passed through the junction during the aggregate period. A negative value indicates an increase in entrainment in Georgiana Slough. Reduction in entrainment is not expressed as the change in the absolute number of fish entering Georgiana Slough in each cell between aggregate groups in order to account for sample size differences between aggregate groups.

3.5.2 RESULTS

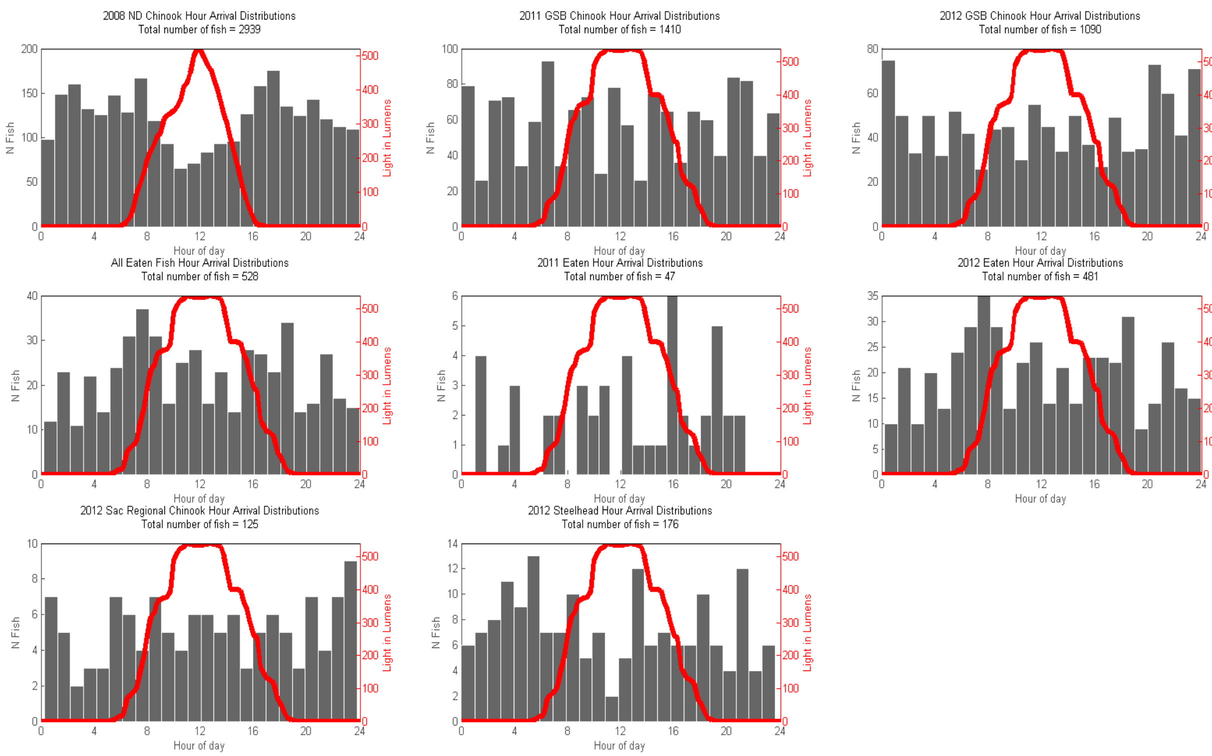
DAY/NIGHT TIMING OF FISH ARRIVAL IN THE JUNCTION AREA

The rigorous covariate assignment process required to support covariate aggregation produces a record of the covariate conditions for each fish when its track or track segment was closest to the CDF point in the junction. This record was used to estimate the frequency distribution of fish arriving in the junction area during each hour of the day to look for differences between the propensity of fish to move downstream during light hours and the propensity of fish to move downstream during dark hours.

Histograms showing the number of fish closest to the CDF point during each hour are displayed for each track group along with a representative light signal for each track group in **Figure 3.5-1**. Because the frequency distribution for the North Delta Study tracks shown in Figure 1 was computed using a value for each track segment rather than a single value for each tag code, it contains multiple values for tracks that were segmented in the junction area, and as a result, this distribution could be biased by the segmentation process. In order to get an unbiased estimate of the arrival time distribution for fish from the North Delta Study, the frequency distribution of the hour that fish were first detected upstream of the DCC was calculated for each track prior to segmentation (**Figure 3.5-2**). These figures illustrate several important points:

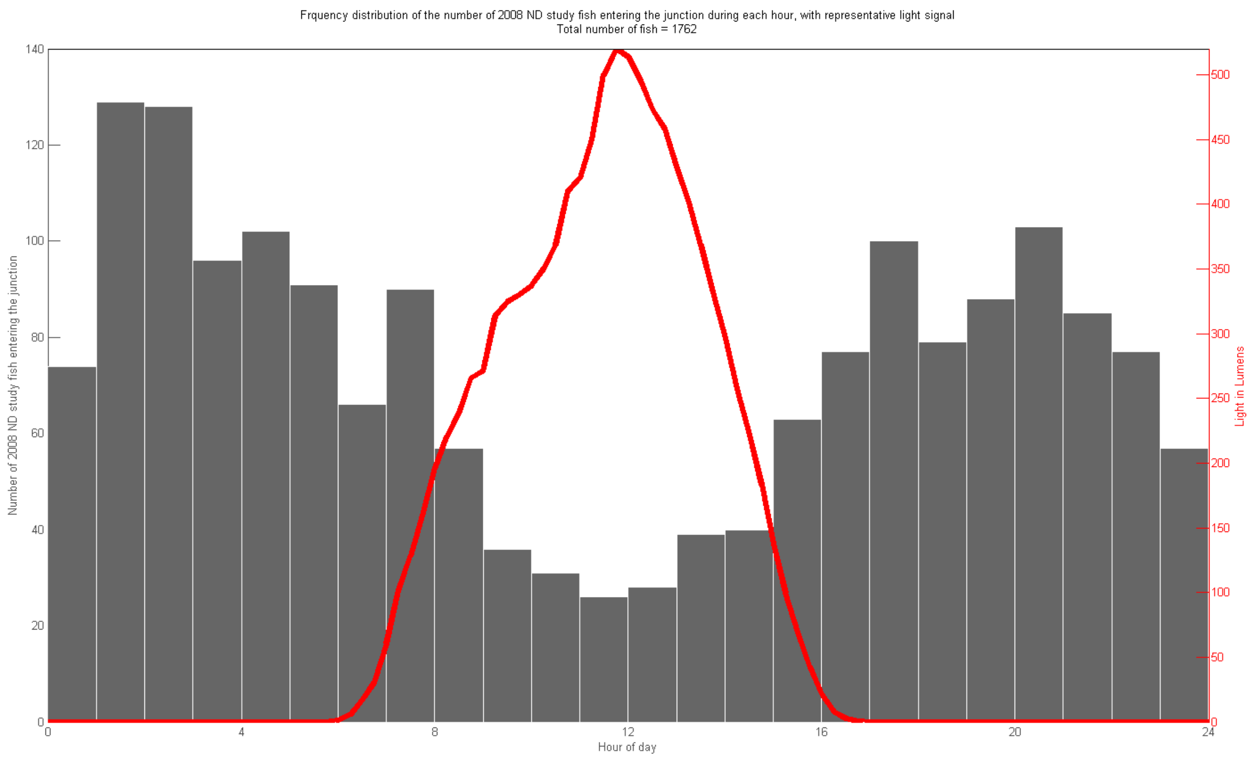
- Fish released during the North Delta Study were much more likely to enter the array during dark or crepuscular hours than during daylight hours. This finding is consistent with data collected during the 2001 and 2003 DCC Studies (Blake and Horn 2003, 2006), and is consistent with the hypothesis that outmigrating juvenile Chinook salmon tend to hold for a portion of daylight hours and then move downstream during dark or crepuscular periods;
- Fish released during the 2012 and 2011 GSNPB studies that were not classified as having been eaten had nearly uniform arrival hour distributions; thus, releasing fish in the Sacramento River immediately downstream of Steamboat Slough for the 2012 and 2011 GSNPB studies likely biased the arrival time distribution over run-of-the-river fish;
- The arrival hour distribution for Chinook salmon tags classified as eaten shows significantly greater predation (number of fish classified as eaten) during crepuscular periods;
- The steelhead tags recorded in the array were more likely to enter the array during dark or crepuscular periods than during light periods; and
- SRCSD tags were more likely to enter the array during evening dark periods and during light periods than during morning dark periods, but this effect may be due to a small sample size for these tags.

There are many factors that could contribute to the differences in the arrival time distributions between the North Delta Study fish and the 2012 GSNPB Study fish, but given that the North Delta Study arrival time distribution is consistent with data from other studies where the release point was significantly upstream of the study area (Chapman et al. 2013), it is likely that some of the difference in the arrival time distributions can be attributed to the fact that the 2008 North Delta Study fish spent several days in the Sacramento River after being released before reaching the junction area, while many 2012 GSNPB Study fish reached the junction within hours of being released.



Notes: Frequency distribution of the hour each tag code was first detected upstream of the DCC during the North Delta Study. Note that this distribution contains one value for each tag code detected, while the frequency distributions for arrival hour at Georgiana Slough contain information for each track segment.

Figure 3.5-1 **Histograms Showing the Frequency Distributions of Entrainment Hour for Each Track Set with Representative Light Curve**



Notes: Frequency distribution of the hour each tag code was first detected upstream of the DCC during the North Delta Study. Note that this distribution contains one value for each tag code detected, while the frequency distributions for arrival hour at Georgiana Slough contain information for each track segment.

Figure 3.5-2 **Histogram Showing the Frequency Distribution of the Hour Each Track Entered the 2008 Walnut Grove Array above the DCC with Representative Light Signal**

JUNCTION WATER VELOCITY CONDITIONS EXPERIENCED BY EACH RELEASE GROUP

The data used to create arrival time distributions for the track groups were also used to create frequency distributions of the junction water velocity conditions encountered by each release group. Histograms showing the frequency distributions of water velocity covariate values are shown for each release group in **Figure 3.5-3**, and the frequency distributions of the junction water velocity conditions encountered by track segments from the North Delta Study are shown separately for light and dark conditions in **Figure 3.5-4**. These figures illustrate several important points:

- Fish experienced a wide range of water velocity conditions during the 2008 North Delta Study, and roughly 30 percent of all track segments passed through the junction during reversing, converging, or slack tide conditions. The range of water conditions that fish experienced during the North Delta Study is indicative of the range of conditions that fish are likely to encounter in the Walnut Grove area in: 1) the fall and winter during normal Sacramento River flows; or 2) during drought conditions throughout the outmigration period;
- Due to the high flows during the 2011 GSNPB Study period, fish that passed through the junction during this study encountered a narrow range of ebb tide conditions, and the location of the critical streakline in the junction was near the left bank and relatively static throughout the study; and
- Fish from the 2012 GSNPB Study encountered a wider range of water velocity conditions than fish released during the 2011 GSNPB Study, but many of the fish that passed through the junction during water velocity conditions that were not encountered by fish in the 2011 GSNPB Study were classified as predators. All but one of the 2012 GSNPB Study fish that passed through the junction during reversing, converging, or slack water periods were classified as predators. As a result, the frequency distributions for GSNPB Study fish classified as predators more closely resemble the frequency distributions for the North Delta Study fish than the frequency distribution of GSNPB Study fish that were not classified as predators.

The frequency distributions in **Figure 3.5-4** show that most of the North Delta Study fish that passed through the junction during daylight hours did so during reversing or converging velocity conditions, whereas fish that passed through the junction during dark periods experienced the full range of water velocity conditions.

It is possible that all of the 2012 GSNPB Study fish that entered the junction during non-ebb tide conditions were eaten by predators, but it is also possible that many of these fish were actually juvenile Chinook salmon that were classified as predators because they produced tracks that did not match human expectations for "normal" downstream movement. This uncertainty highlights the difficulty in developing predator classification schemes for tidally forced junctions where a broad range of water velocity conditions occur, and this difficulty demonstrates the potential value of high resolution water velocity maps than can be used to assist predator classification efforts.

The frequency distribution of water velocity conditions for predators or fish holding in the array should be fairly uniform because the time when these fish were closest to the CDF point is likely to be due to random chance rather than a propensity to move through the junction during specific conditions. The ebb tide frequency distribution for North Delta Study fish during daylight conditions is consistent with this expectation, but the much larger number of fish that were closest to the CDF point in daylight hours during flood and converging flow conditions is not. For this reason, it is likely that many of the fish closest to the CDF point during daylight flood and converging flows are outmigrants, while a greater proportion of the fish closest to the CDF point during daylight ebb conditions are not displaying outmigration behavior (e.g., predators, holding juveniles, etc.). If this is true, then it means that almost all of the outmigrants that entered into Georgiana Slough junction did so in the daylight during flood and converging conditions.

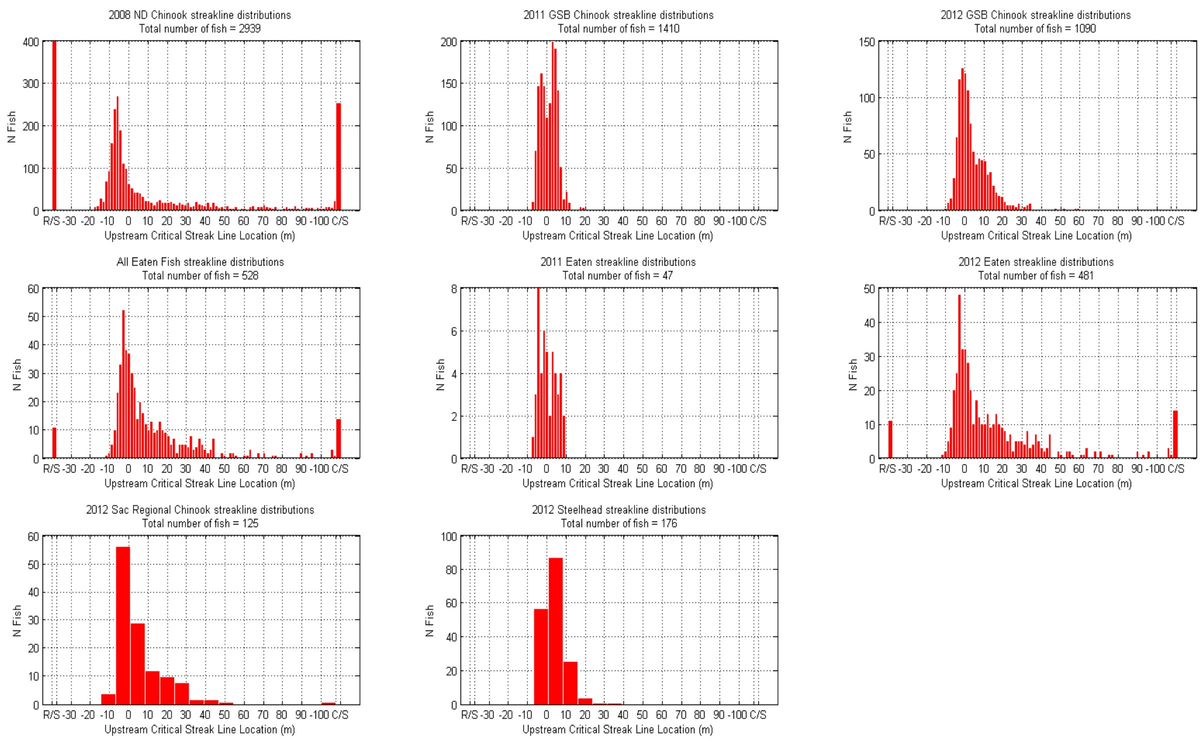


Figure 3.5-3 **Histograms Showing the Frequency Distribution of Water Velocity Covariate Values for Each Track Set**

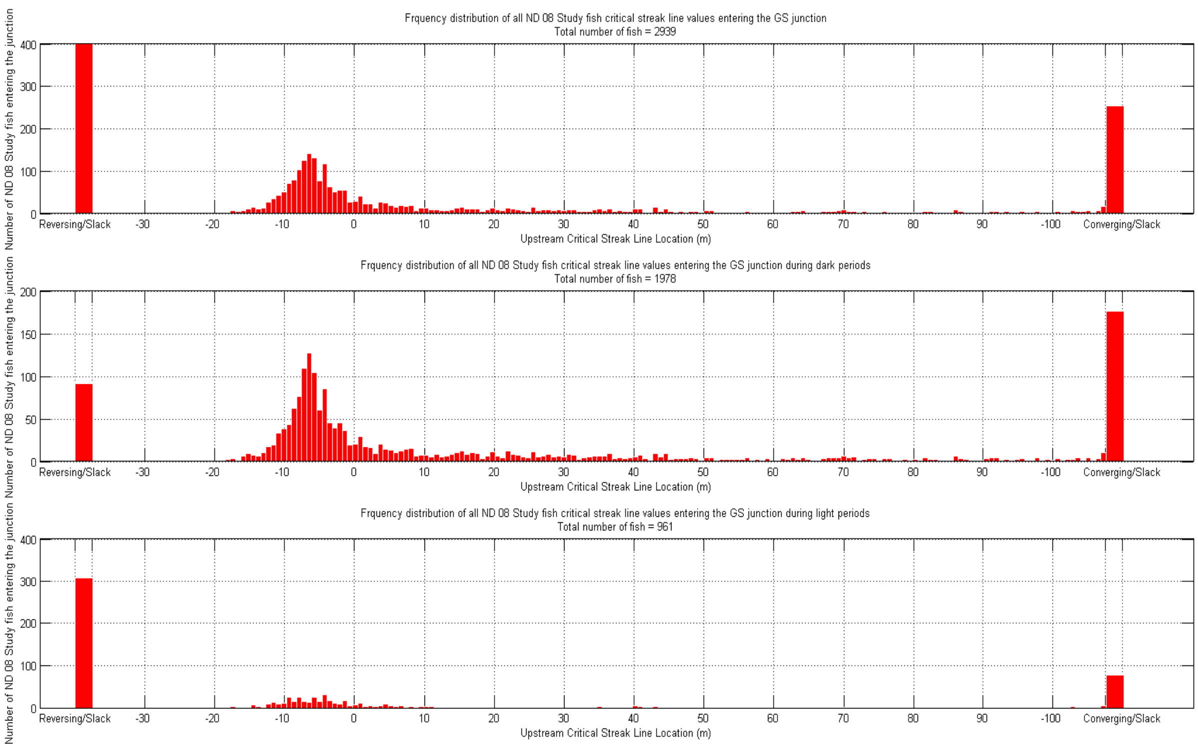


Figure 3.5-4 **Histograms Showing the Distribution of Water Velocity Covariate Values for the 2008 Track Segments Broken Down by Light**

ENTRAINMENT RATES AND OVERALL ENTRAINMENT FOR EACH COVARIATE PERIOD

The overall entrainment rate (fraction of all fish entering the junction for a covariate period entrained in Georgiana Slough), and the total entrainment (absolute number of fish entrained in Georgiana Slough) was calculated for each covariate group, and these entrainment metrics were plotted as a function of water velocity condition in **Figure 3.5-5** and **Figure 3.5-6**. The entrainment rate plot shown in **Figure 3.5-5** illustrates how entrainment risk changes as tidal forcing changes the velocity patterns in the junction area. The plots of total entrainment shown in **Figure 3.5-6** show the contribution of each tidal velocity group to the overall entrainment for a set of fish. The total entrainment curve for each group can be thought of as the product of the total risk for each release group multiplied by the number of fish exposed to that risk, and illustrates the combined effect of near-field processes that determine entrainment risk for each velocity condition, and upstream processes that determine how many fish arrive during each condition. Key points illustrated by these plots are:

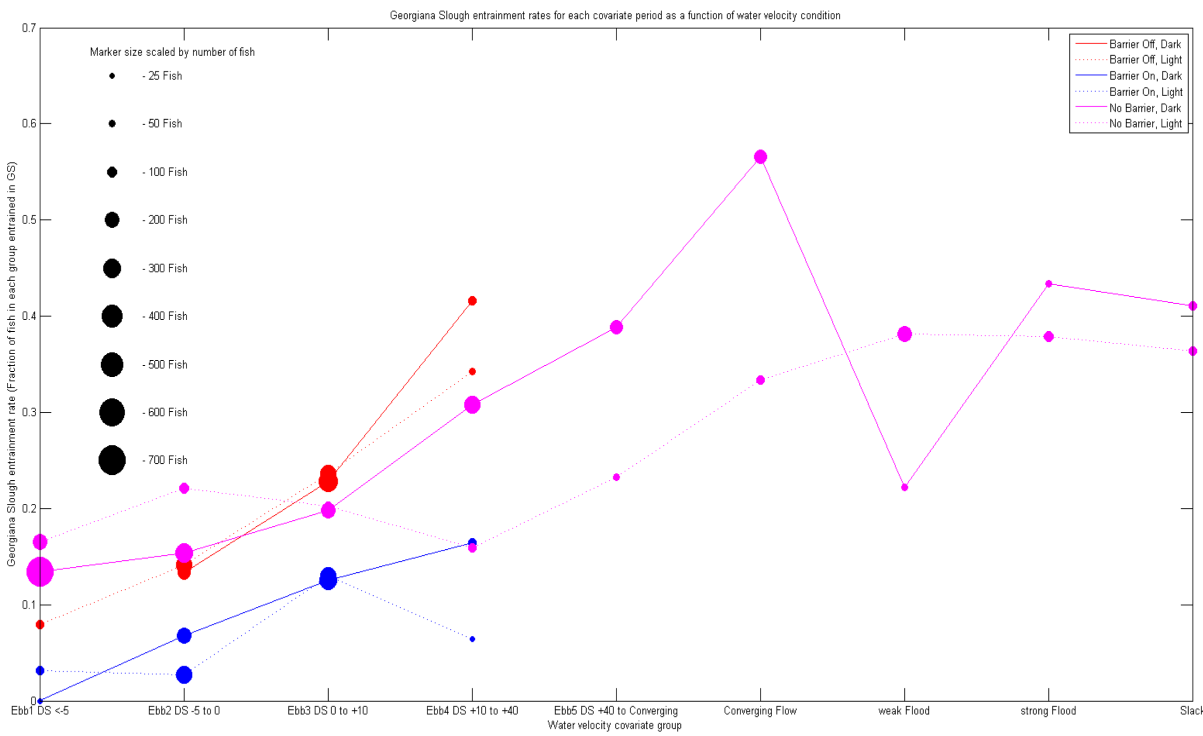
- The entrainment rate curve for dark and light periods during the North Delta Study shows that entrainment rates change significantly throughout the tidal cycle, with entrainment rates increasing with increasing downstream and upstream critical streakline values;
- The entrainment rate curves for fish from the GSNPB studies show a similar positive relationship between entrainment rates and downstream critical streakline values;
- Differences between the entrainment rate curves for the barrier during light and dark periods indicate that during Ebb2 and Ebb4 water velocity conditions the BAFF was less effective during dark periods than during light periods. This difference is explored in more detail in following sections; and
- Differences between the entrainment rate curves for periods when the barrier was off and periods when the barrier was out indicate that during Ebb3 and Ebb4 conditions fish were entrained at a higher rate when the barrier is installed and off than when the barrier is out. This is explored in more detail in the section on barrier effects.

Due to the high Sacramento River discharge during the 2012 GSNPB Study and the 2011 GSNPB Study, the BAFF has been evaluated during periods when entrainment rates without the BAFF are near the lowest observed during the North Delta Study. Further, the total entrainment curves shown in **Figure 3.5-6** suggests that most of the fish from the 2012 GSNPB and 2011 GSNPB studies entrained in Georgiana Slough were entrained during water velocity periods that had a relatively small effect on the overall entrainment of fish during the North Delta Study.

The total entrainment curve for the North Delta Study indicates that fish moving through the junction during light periods contribute very little to the overall entrainment during this study, except during flood tide conditions. This observation supports the idea that many of the fish in the junction during daytime flood conditions are outmigrants, while a larger proportion of fish in the array during daylight ebb conditions are predators or juveniles holding in the array.

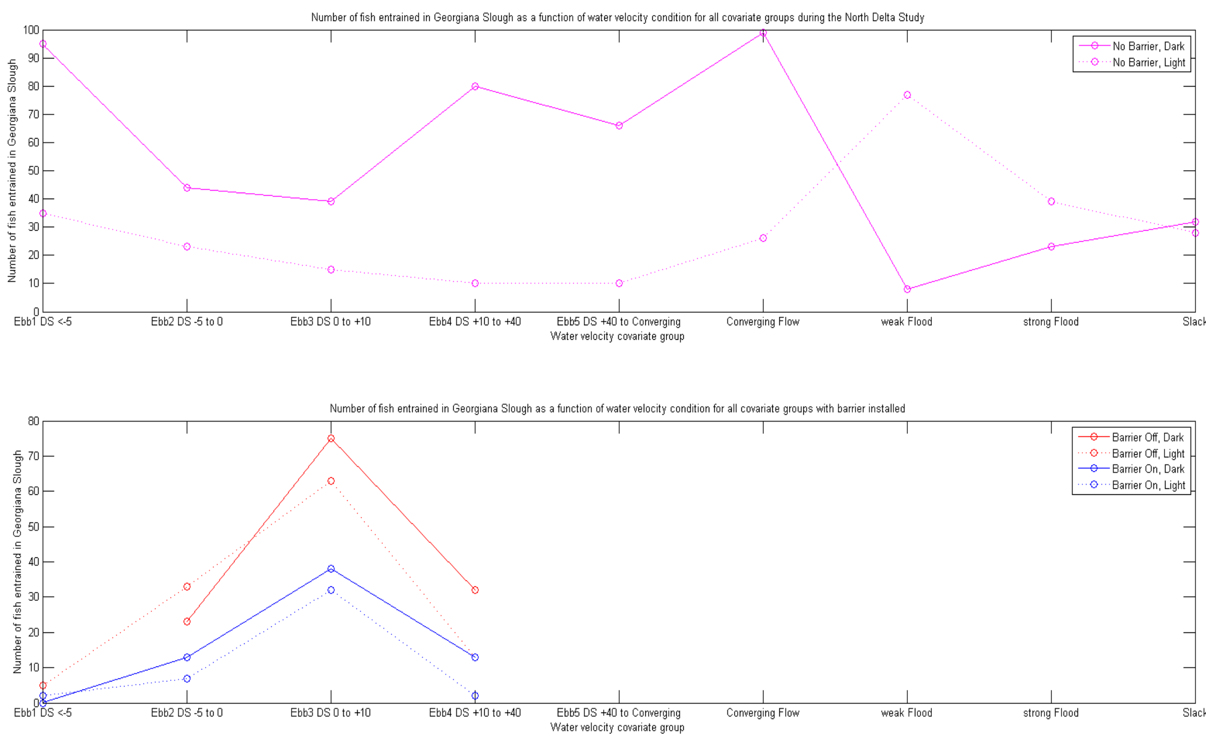
The total entrainment curves for the North Delta Study show that converging flow periods and reversing flow periods have a significant impact on overall entrainment in Georgiana Slough when Sacramento River discharge is low enough for regular flow reversals in the Walnut Grove area.

The entrainment rate and total entrainment plots illustrate the significant impact that converging and reversing flow conditions have on total entrainment in Georgiana Slough during periods of low Sacramento River discharge, and highlight our lack of data on the BAFF's performance during the velocity conditions that had the greatest effect on entrainment during the North Delta Study. Given the percentage of total entrainment due to reversing and converging flow conditions under low discharge conditions, it is worth noting that USGS flow station data suggests that closing the DCC increases the frequency and duration of these conditions at the Georgiana Slough junction (**Appendix F**).



Notes: Light period and dark period entrainment rate curves plotted for each track group as a function of water velocity covariate. The size of the markers indicate the number of fish in each covariate group, the marker scale is shown on the top left of the figure.

Figure 3.5-5 **Plot of Overall Entrainment Rate in Georgiana Slough for each Covariate Period**



Notes: Light period and dark period entrainment rate curves plotted for each track group as a function of water velocity covariate. The size of the markers indicate the number of fish in each covariate group, the marker scale is shown on the top left of the figure.

Figure 3.5-6 **Plots Illustrating Entrainment Rates Changing with Tides**

SPATIAL DISTRIBUTIONS OF FISH DENSITY AND ENTRAINMENT RATES FOR ALL COVARIATE PERIODS

The entrainment rate and total entrainment curves shown in **Figure 3.5-5** and **Figure 3.5-6** provide an estimate of the relationship between the junction velocity patterns as quantified by the upstream and downstream critical streakline values, and the entrainment of outmigrating juvenile Chinook salmon in Georgiana Slough. The purpose of the following spatial analysis sections is to explore *why* the observed entrainment rates occurred for each set of junction velocity conditions, and to understand how the barrier affects the movement and entrainment of outmigrants within the junction area. Broadly speaking, the BAFF can change entrainment in the junction in two ways: the barrier can change the distribution of fish within the junction, and the barrier can change entrainment rates within the junction area. The spatial distribution of entrainment rates within the junction is calculated by dividing the number of fish that pass through a given grid cell that go into Georgiana Slough by the total number of fish that pass through that cell. Thus, the BAFF can reduce the number of fish entering Georgiana Slough by moving fish away from areas of high entrainment, lowering the entrainment rate in areas that contain large numbers of fish, or through a combination of these effects. Likewise, other covariates, such as water velocity patterns or light, can increase or decrease total entrainment by changing entrainment rates or fish distributions. For this reason, plots showing the spatial distribution of fish density and entrainment rates in the junction area for different covariate groups are useful for understanding why each covariate changes entrainment in Georgiana Slough.

Plots showing the spatial distribution of fish in the junction area are provided in **Figures 3.5-7** through **3.5-12**. The orientation of the plots is downstream-facing with Georgiana Slough diverging to the left and the Sacramento River turning to the right. These plots display the spatial distribution of fish that share each fate as a separate surface so that it easier to see how fish with each fate are distributed through the junction area for each set of water velocity conditions. Plots of the spatial distribution of the Georgiana Slough entrainment rate in the junction area for each covariate group are shown in **Figures 3.5-13** through **3.5-21**. The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. These figures also show the location of the BAFF, and the approximate range of critical streakline locations within the river cross section for downstream (south) flow conditions. In order to improve the spatial resolution of the estimated entrainment rate distributions for converging and reversing conditions, tracks from light and dark periods during the North Delta Study were combined to calculate the distributions shown in **Figure 3.5-15**, **Figure 3.5-16**, and **Figure 3.5-17**.

These plots provide an enormous amount of information on the mechanics of juvenile salmon entrainment in Georgiana Slough, and comparisons between sets of plots can illustrate the effects of a variety of covariates on the processes that control entrainment in Georgiana Slough. The most important features illustrated by these figures are:

- Fish mass is not uniformly distributed in the river cross-section, and likewise, fish entrained in Georgiana Slough is not uniformly distributed in the river cross-section. This means that the entrainment of outmigrants is dependent on velocity patterns in the junction, and that the percentage of fish entrained in Georgiana Slough is not identically equal to the percentage of water entrained in Georgiana Slough.

For North Delta Study dark periods, the distribution of fish sharing each fate changed significantly over the range of tidal velocity patterns:

- The portion of the river cross- section upstream of the junction contributing fish to Georgiana Slough increased as the critical streakline moved further to river right upstream of the junction (e.g. during lower Sacramento River inflows);

- During converging flow conditions fish entered Georgiana Slough from all regions in the junction, as expected. With the DCC gates closed, converging conditions last longer and are stronger than when the gates are open (**Appendix F**);
- During weak flood tide conditions fish entered Georgiana Slough from the river left half of the Sacramento River, while the river right half of the Sacramento River contained fish still moving downstream. This observation is consistent with hydrodynamic measurements that show that the river left half of the Sacramento River reverses before the river right half;
- During strong flood tide conditions fish in the entire portion of the Sacramento River cross-section entered Georgiana Slough, while fish upstream of Georgiana Slough exited the junction moving upstream; and
- During slack conditions fish with each fate were distributed throughout the junction area.

For North Delta Study fish moving during dark periods, the point in the river cross-section where entrainment in Georgiana Slough dropped below 50 percent was located very close to the lower critical streakline boundary for each ebb covariate group. This observation supports the use of flow ratios and critical streakline values (**Appendix F**) to estimate effects of velocity patterns on juvenile entrainment in river junctions.

The spatial distributions of fish and entrainment rates for ebb conditions during North Delta Study daylight periods were very different from the spatial distributions from ebb conditions during North Delta Study dark periods; during the day fish were more uniformly distributed in the study area and entrainment rates were lower and more uniformly distributed. These differences support the idea that many of the fish in the array during North Delta Study daylight ebb periods are not actively outmigrating; rather, they may be holding.

The spatial distributions of fish and entrainment rates during North Delta Study flood and converging flow conditions were similar for light and dark periods, which suggests that many of the fish that enter the junction during reversing and converging flows behave similarly regardless of the light conditions. This observation supports the idea that most of the fish in the array during North Delta Study daylight flood and converging periods are outmigrating.

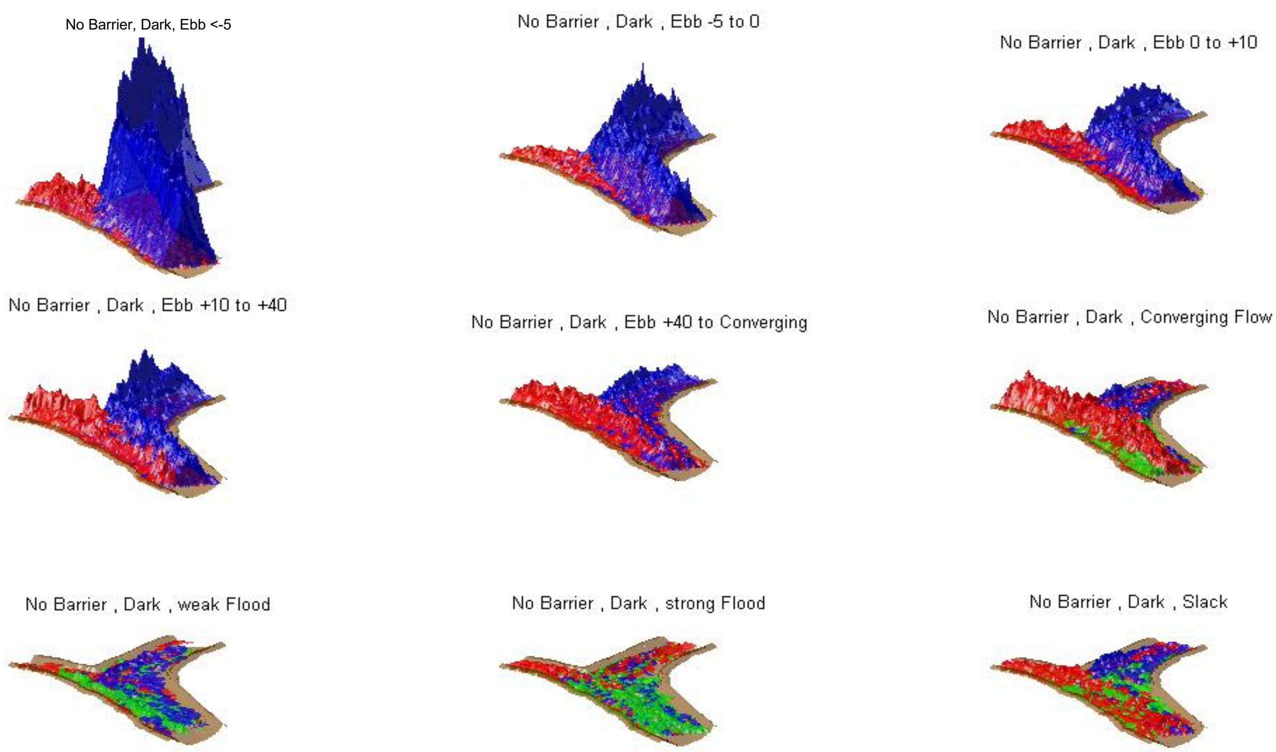
The spatial distribution of fish entering Georgiana Slough during periods when the BAFF was installed showed a similar trend between increasing critical streakline values and an increase in the amount of the Sacramento River cross section that contributed fish to Georgiana Slough, though there was less overlap in the areas used by fish that entered Georgiana Slough and areas where fish continued downstream in the Sacramento River.

The spatial distribution of entrainment rates for periods when the barrier was installed show similar relationships between the location of the critical streakline and the location of the interface between areas of high Georgiana Slough entrainment and areas of low Georgiana Slough entrainment, but the spatial gradients in entrainment rate are much higher with the barrier installed. These spatial gradients were higher when the BAFF was on than when it was off. The increase in spatial gradients during BAFF On periods is partially due to the fact that fish tracks exhibiting unusual behaviors were removed by the predator classification process, so these spatial gradients are not diluted with information from fish that are not outmigrating.

In general, operating the barrier decreased the number of fish entering Georgiana Slough, decreased the extent of the Sacramento River cross-section contributing fish to Georgiana Slough, and increased the density of fish along the face of the BAFF and in the areas in the Sacramento River just downstream of the BAFF. These effects are explored in more detail in the next section.

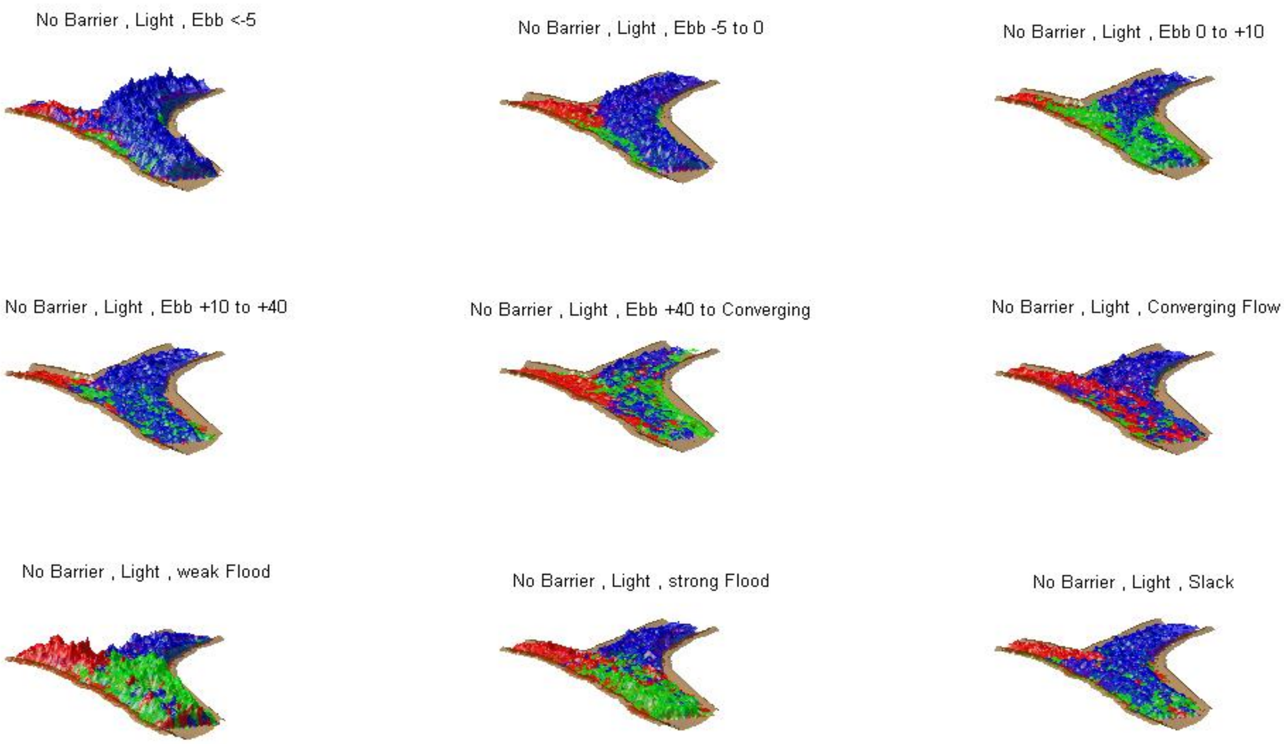
In general, the distribution of fish and entrainment rates was very similar between light and dark conditions when the BAFF was off and when the BAFF was on. The exception is that there are several interesting differences in the effect of the barrier during light and dark conditions for the Ebb2 and Ebb3 periods; during dark periods barrier operations appear to shift fish densities away from the barrier, while at the same time, the entrainment rate upstream of the barrier is higher when the barrier is on during dark periods than when the barrier is on during light periods. These effects are explored in more detail in the following sections.

This page intentionally left blank.



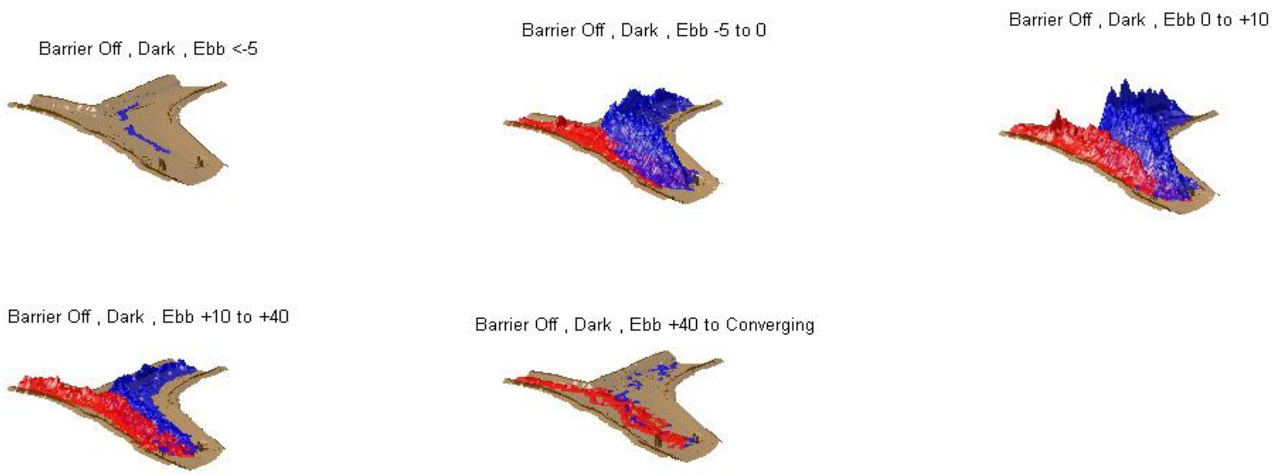
Notes: Empirical fish density distributions for each junction fate: The height of the red surface indicates the number of fish that exited the junction via Georgiana Slough in each portion of the junction, the height of the blue surface indicates the number of fish that exited the junction moving downstream in the Sacramento River in each portion of the junction, and the height of the green surface indicates the number of fish that exited the junction moving upstream in the Sacramento River in each portion of the junction. The junction bathymetry is represented by the brown surface. For clarity, the green surface showing the spatial distribution of upstream exiting fish is not show for the Ebb conditions, so that the near-bank distribution of Georgiana Slough exiting fish is easier to see. It is likely that the near-shore mass of fish exiting the junction moving upstream during dark ebb conditions is caused by predators, or juveniles displaying holding behavior during crepuscular periods.

Figure 3.5-7 **Spatial Distribution of Fish Entering the Junction during Dark Periods with the Barrier Out**



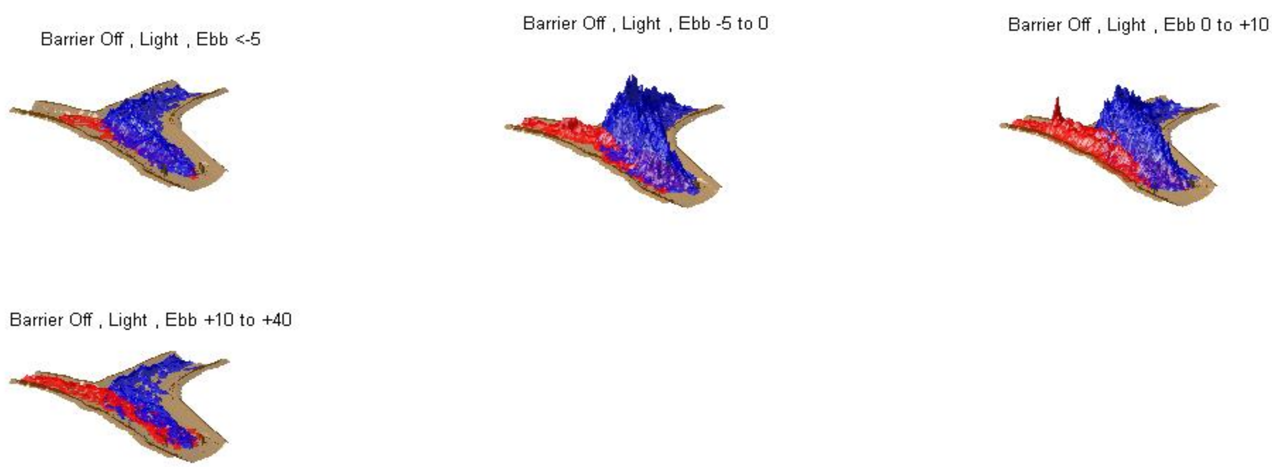
Empirical fish density distributions for each junction fate: The height of the red surface indicates the number of fish that exited the junction via Georgiana Slough in each portion of the junction, the height of the blue surface indicates the number of fish that exited the junction moving downstream in the Sacramento River in each portion of the junction, and the height of the green surface indicates the number of fish that exited the junction moving upstream in the Sacramento River in each portion of the junction. The junction bathymetry is represented by the brown surface.

Figure 3.5-8 **Spatial Distribution of Fish Entering the Junction during Light Periods with the Barrier Out**



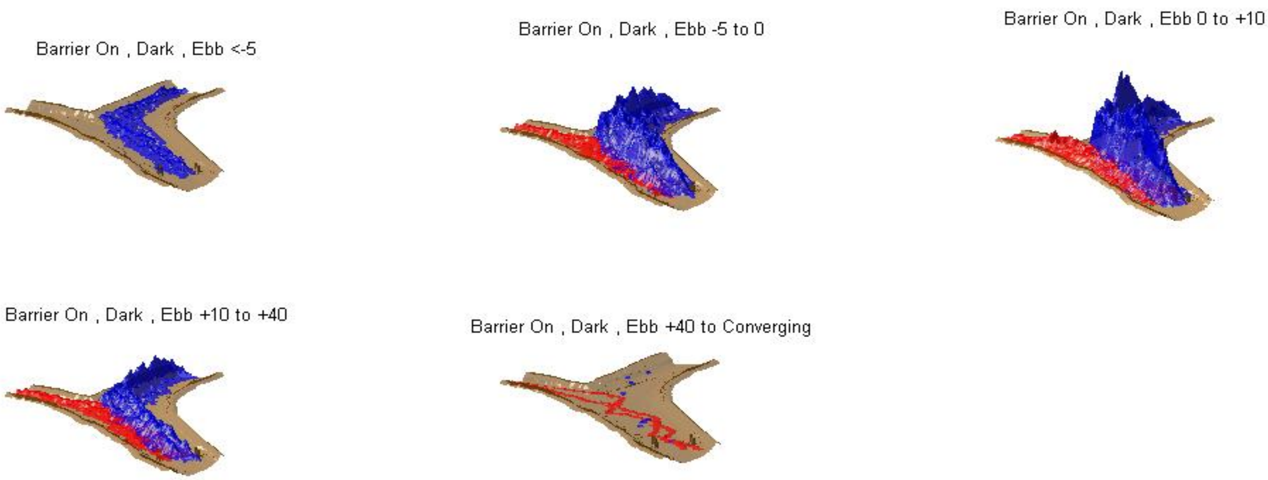
Empirical fish density distributions for each junction fate: The height of the red surface indicates the number of fish that exited the junction via Georgiana Slough in each portion of the junction, and the height of the blue surface indicates the number of fish that exited the junction moving downstream in the Sacramento River in each portion of the junction. The junction bathymetry is represented by the brown surface.

Figure 3.5-9 **Spatial Distribution of Fish Entering the Junction during Dark Periods with the Barrier Installed and Off**



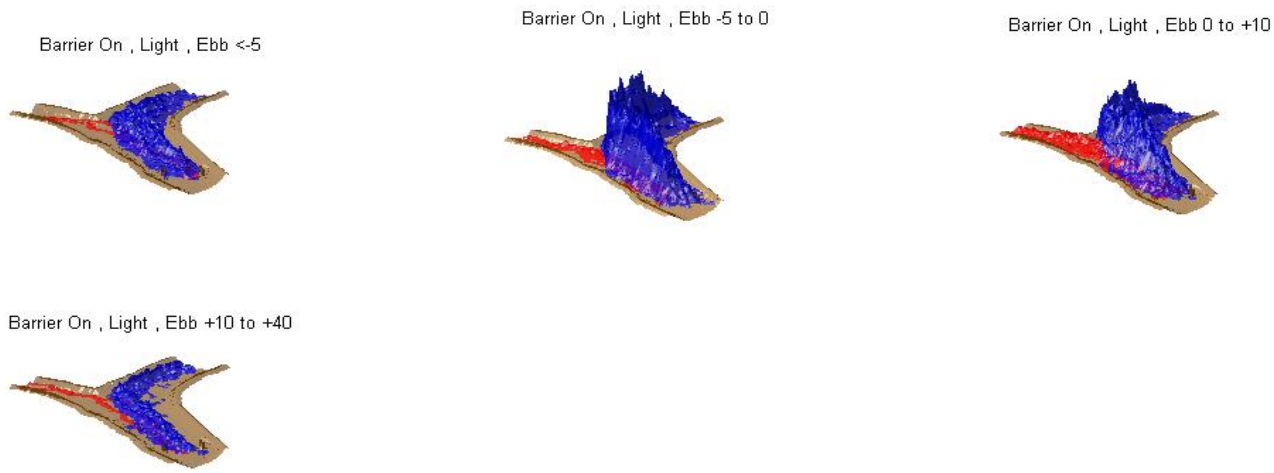
Empirical fish density distributions for each junction fate: The height of the red surface indicates the number of fish that exited the junction via Georgiana Slough in each portion of the junction, and the height of the blue surface indicates the number of fish that exited the junction moving downstream in the Sacramento River in each portion of the junction. The junction bathymetry is represented by the brown surface.

Figure 3.5-10 **Spatial Distribution of Fish Entering the Junction during Light Periods with the Barrier Installed and Off**



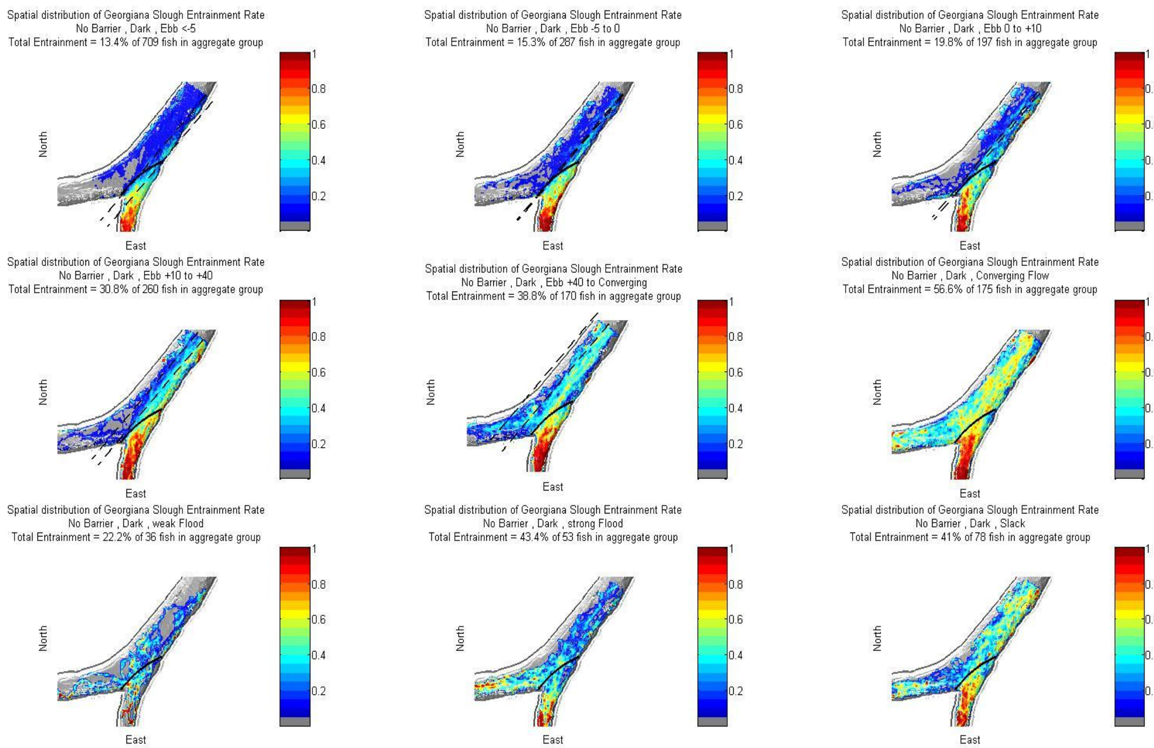
Empirical fish density distributions for each junction fate: The height of the red surface indicates the number of fish that exited the junction via Georgiana Slough in each portion of the junction, and the height of the blue surface indicates the number of fish that exited the junction moving downstream in the Sacramento River in each portion of the junction. The junction bathymetry is represented by the brown surface.

Figure 3.5-11 **Spatial Distribution of Fish Entering the Junction during Dark Periods with the Barrier On**



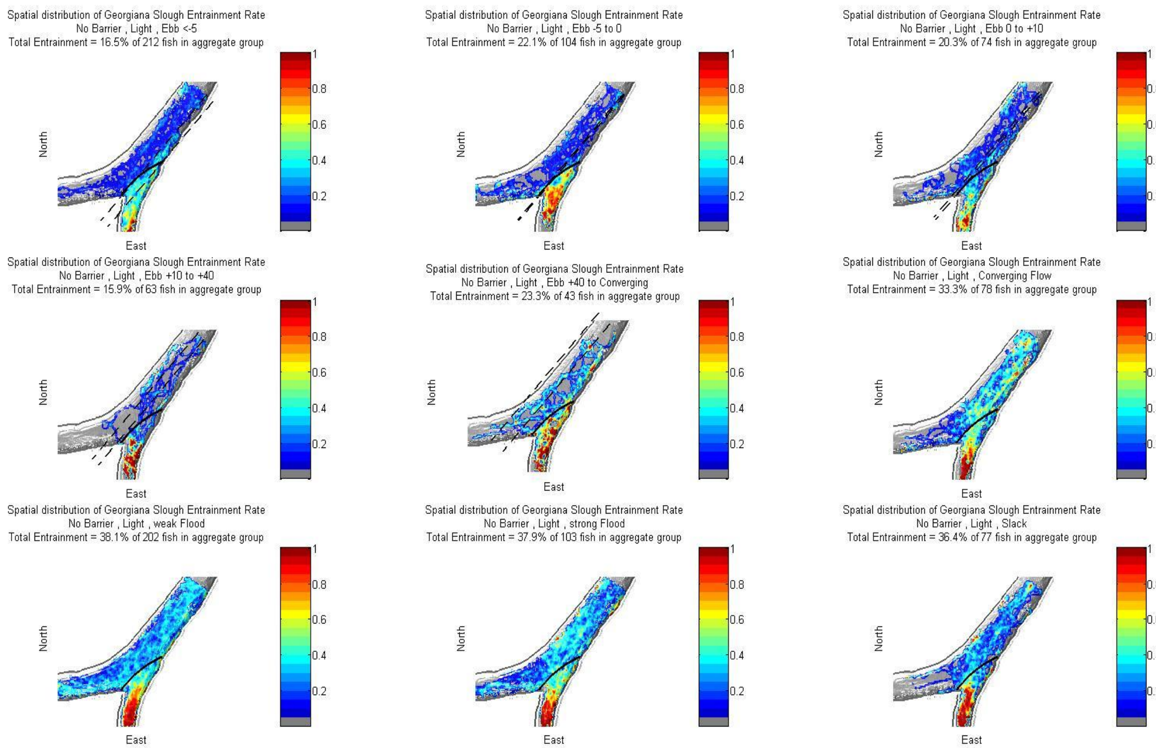
Notes: Empirical fish density distributions for each junction fate: The height of the red surface indicates the number of fish that exited the junction via Georgiana Slough in each portion of the junction, and the height of the blue surface indicates the number of fish that exited the junction moving downstream in the Sacramento River in each portion of the junction. The junction bathymetry is represented by the brown surface.

Figure 3.5-12 **Spatial Distribution of Fish Entering the Junction during Light Periods with the Barrier Installed and On**



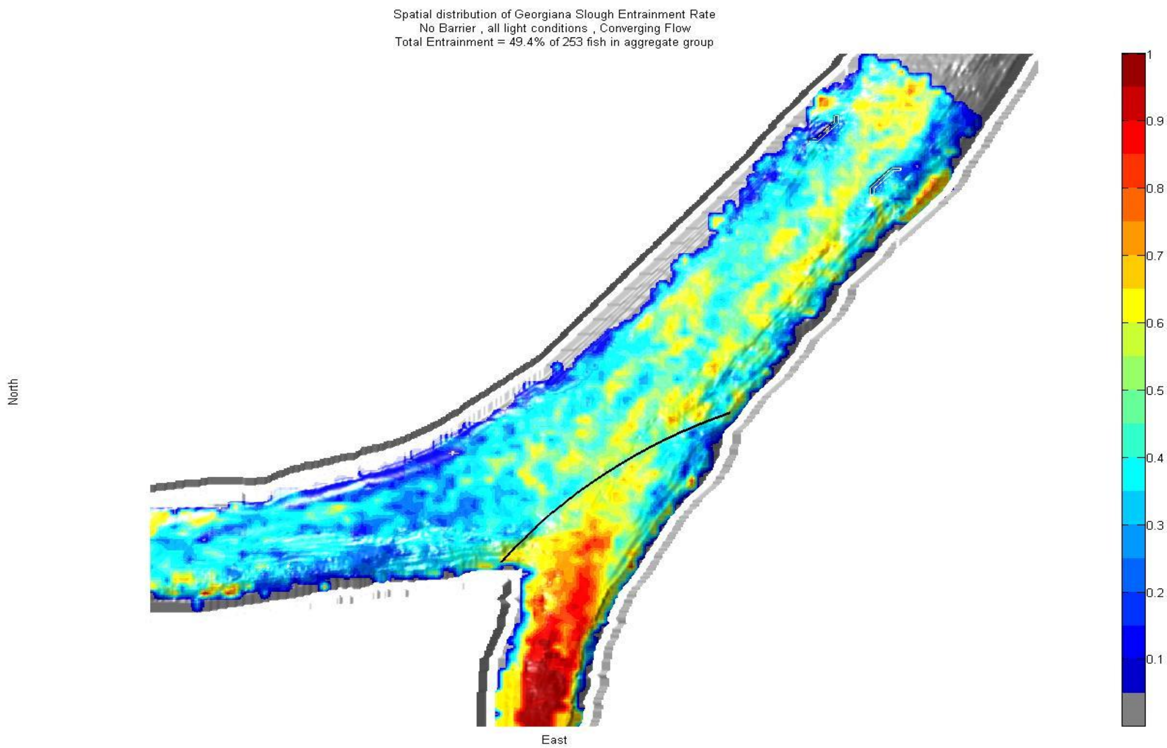
Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Maps showing the spatial distribution of the Georgiana Slough entrainment rate for each water velocity covariate group. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-13 **Spatial Distribution of Georgiana Slough Entrainment Rate during Dark Periods with the Barrier Out**



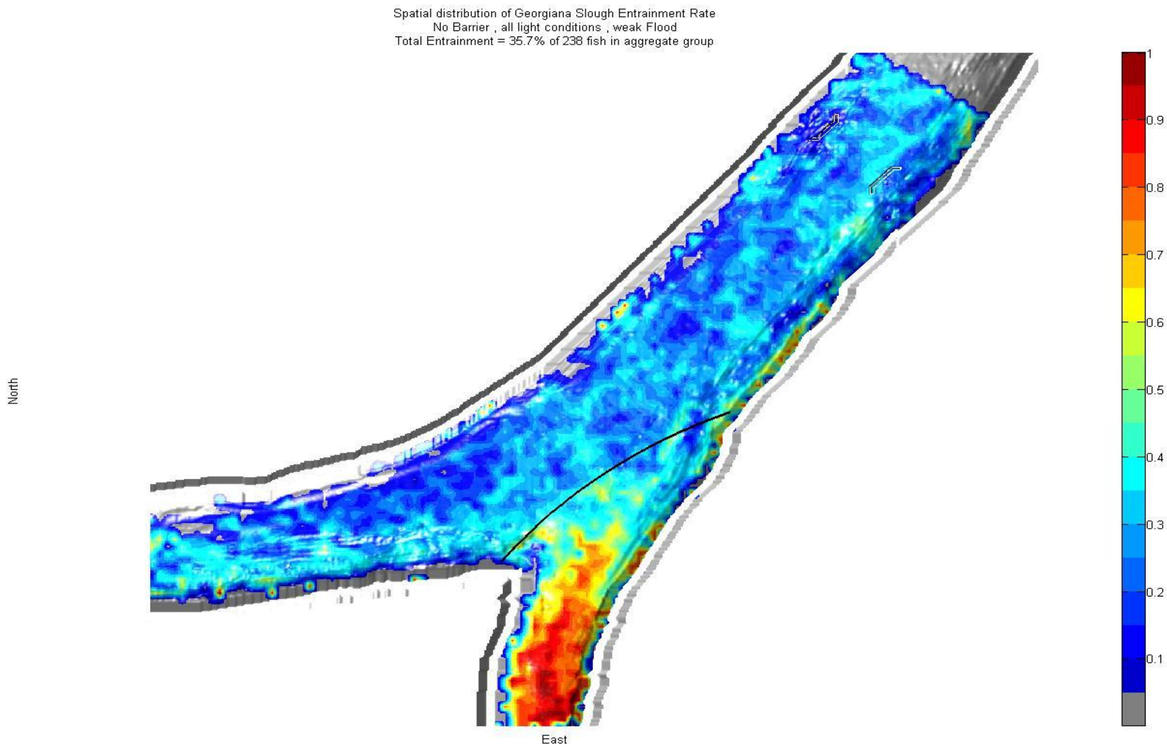
Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Maps showing the spatial distribution of the Georgiana Slough entrainment rate for each water velocity covariate group. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-14 **Spatial Distribution of Georgiana Slough Entrainment Rate during Light Periods with the Barrier Out**



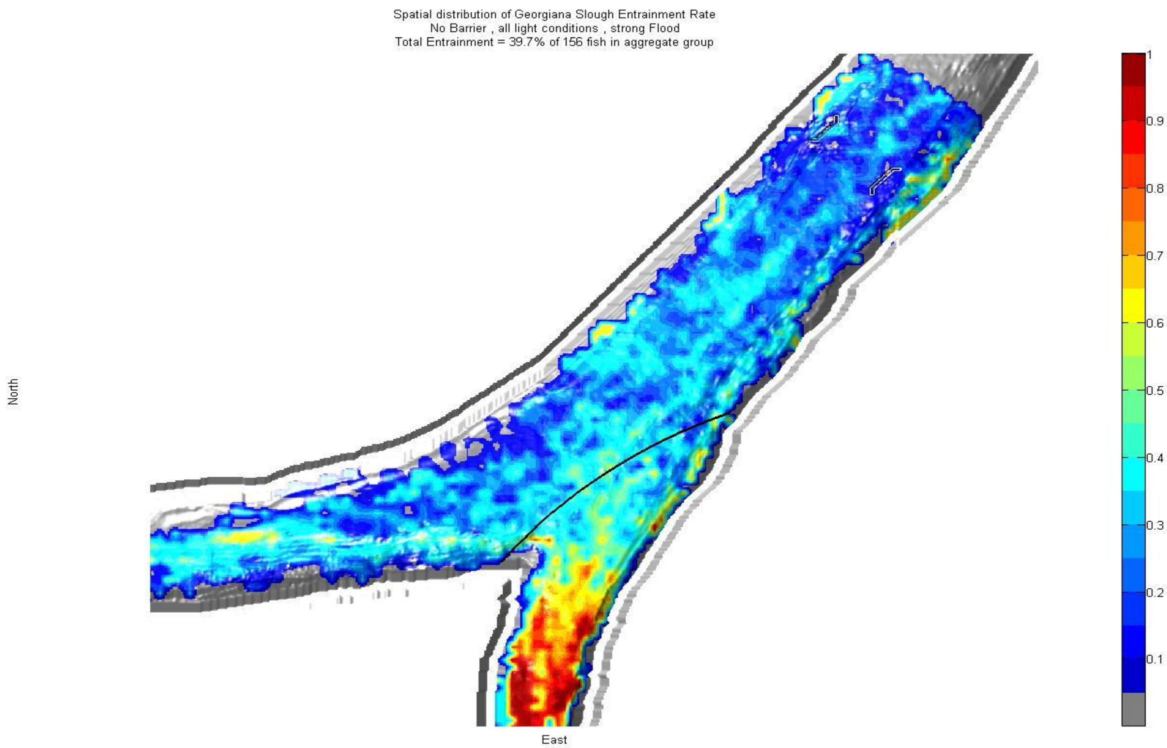
Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Map showing the spatial distribution of the Georgiana Slough entrainment rate combining light and dark conditions to increase sample size. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-15 **Spatial Distribution of Georgiana Slough Entrainment Rate for Converging Flow Combining Tracks From all Light Levels**



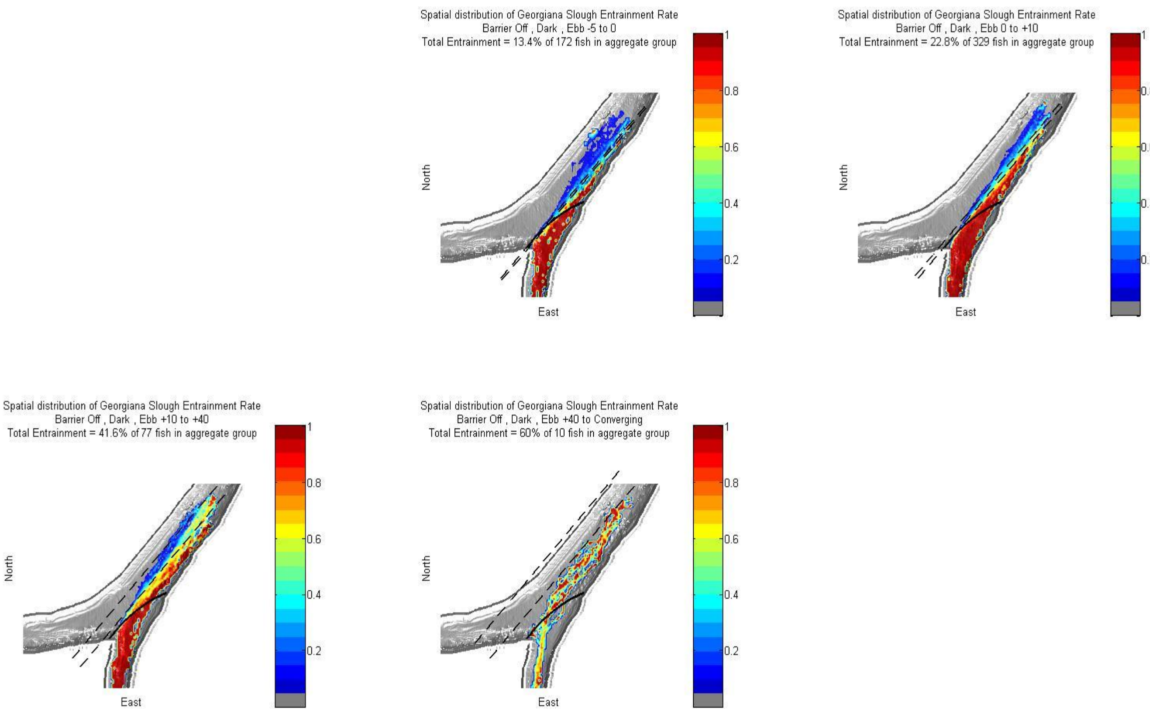
Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Map showing the spatial distribution of the Georgiana Slough entrainment rate combining light and dark conditions to increase sample size. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-16 **Spatial Distribution of Georgiana Slough Entrainment Rate for Weak Flood Conditions Combining Tracks from all Light Levels**



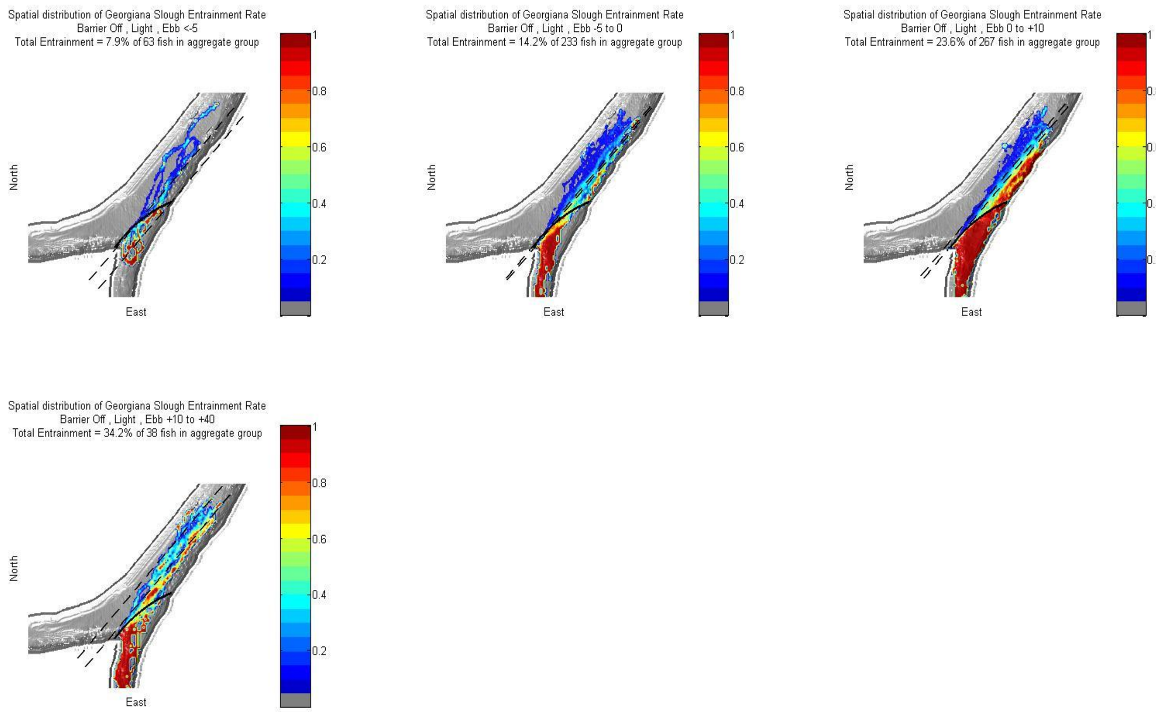
Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Map showing the spatial distribution of the Georgiana Slough entrainment rate combining light and dark conditions to increase sample size. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-17 **Spatial Distribution of Georgiana Slough Entrainment Rate for Strong Flood Conditions Combining Tracks from all Light Levels**



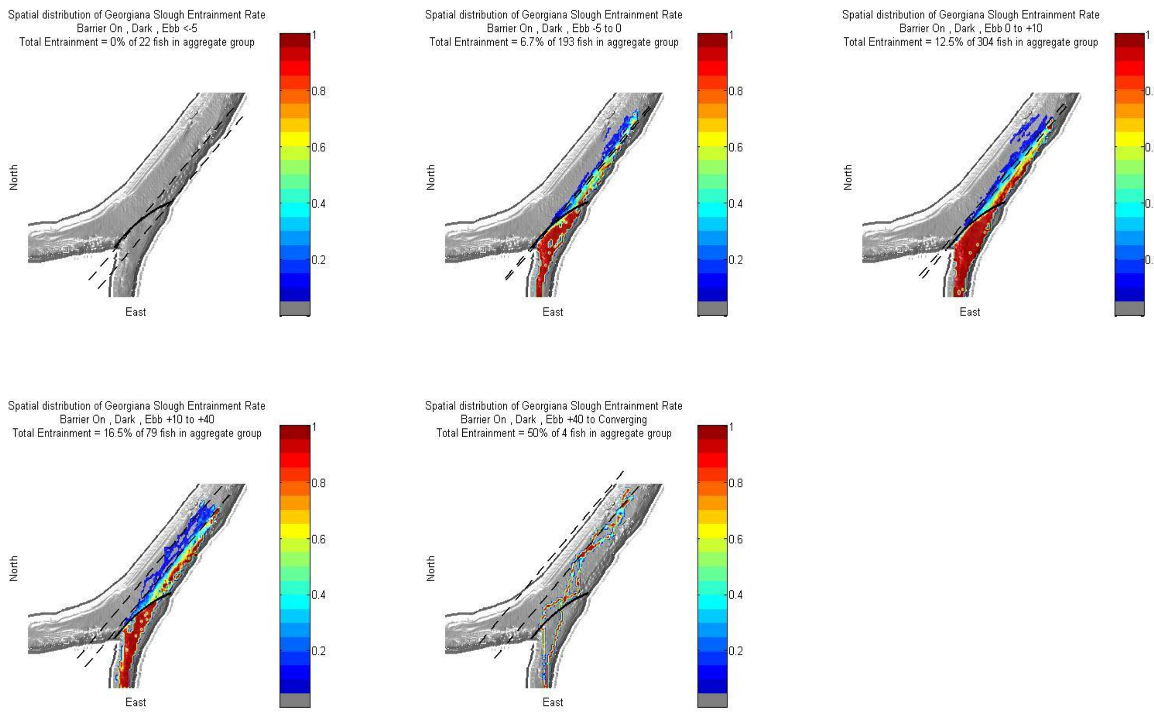
Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Maps showing the spatial distribution of the Georgiana Slough entrainment rate for each water velocity covariate group. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-18 **Spatial Distribution of Georgiana Slough Entrainment Rate during Dark Periods with the Barrier Installed and Off**



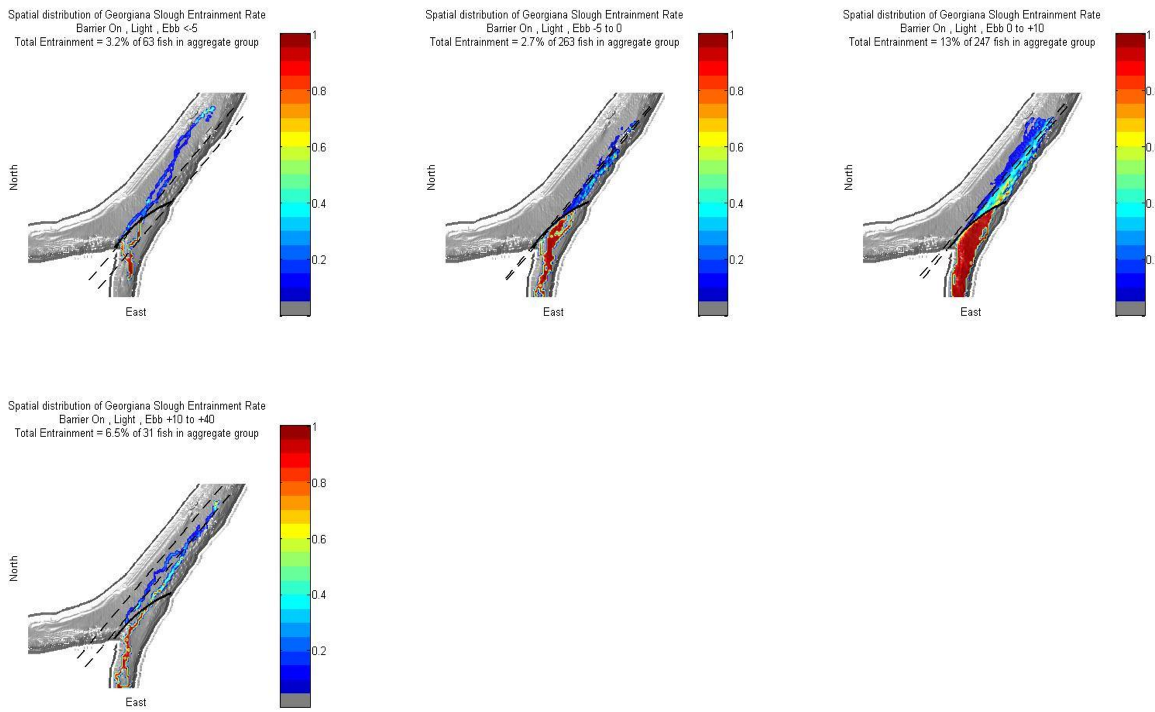
Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Maps showing the spatial distribution of the Georgiana Slough entrainment rate for each water velocity covariate group. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-19 **Spatial Distribution of Georgiana Slough Entrainment Rate during Light Periods with the Barrier Installed and Off**



Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Maps showing the spatial distribution of the Georgiana Slough entrainment rate for each water velocity covariate group. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-20 **Spatial Distribution of Georgiana Slough Entrainment Rate during Dark Periods with the Barrier Installed and On**



Notes: The north and east labels on the plots represent northing (y) and easting (x) coordinates and not actual compass heading points. Maps showing the spatial distribution of the Georgiana Slough entrainment rate for each water velocity covariate group. The bathymetry in the junction area is colored by the Georgiana slough entrainment rate for each grid cell; the color scale is indicated by the accompanying color bars. Areas containing no fish that entered Georgiana Slough are shown in grey. The entrainment rate indicates the fraction of fish in each grid cell that enter Georgiana Slough, this should not be confused with the total number of fish that enter Georgiana Slough; areas with high entrainment might have low fish density, and thus, contribute relatively little to overall entrainment in Georgiana Slough. The location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for ebb covariate periods are shown as dotted black lines.

Figure 3.5-21 **Spatial Distribution of Georgiana Slough Entrainment Rate during Light Periods with the Barrier Installed and On**

EFFECTS OF BARRIER INSTALLATION AND OPERATION ON ENTRAINMENT IN GEORGIANA SLOUGH

In order to explore the effects of the BAFF on the distribution of fish and entrainment rates in more detail, a series of figures were constructed that compared a variety of metrics between tracks that passed through the junction when the BAFF was out during dark periods (North Delta Study outmigrants), tracks that passed through the junction when the BAFF was installed and off, and tracks that passed through the junction when the BAFF was on (**Figure 3.5-22** through **3.5-25**). Tracks from dark and light periods were pooled for BAFF study fish to increase the spatial resolution of statistics for times when the barrier was installed, while tracks from light periods during the North Delta Study were omitted to focus the analyses on the behavior of outmigrants. The first two columns of plots in each figure show the distribution of fish and entrainment rates in the junction area for different barrier conditions (out, off, on); the last column of plots shows the effect of changing the barrier condition on entrainment in Georgiana Slough. These figures illustrate the following points:

- During the ebb tide periods when the barrier was installed, there were very large spatial gradients in the distribution of fish in the cross-stream direction, and these gradients were greatest at the mouth of Georgiana Slough;

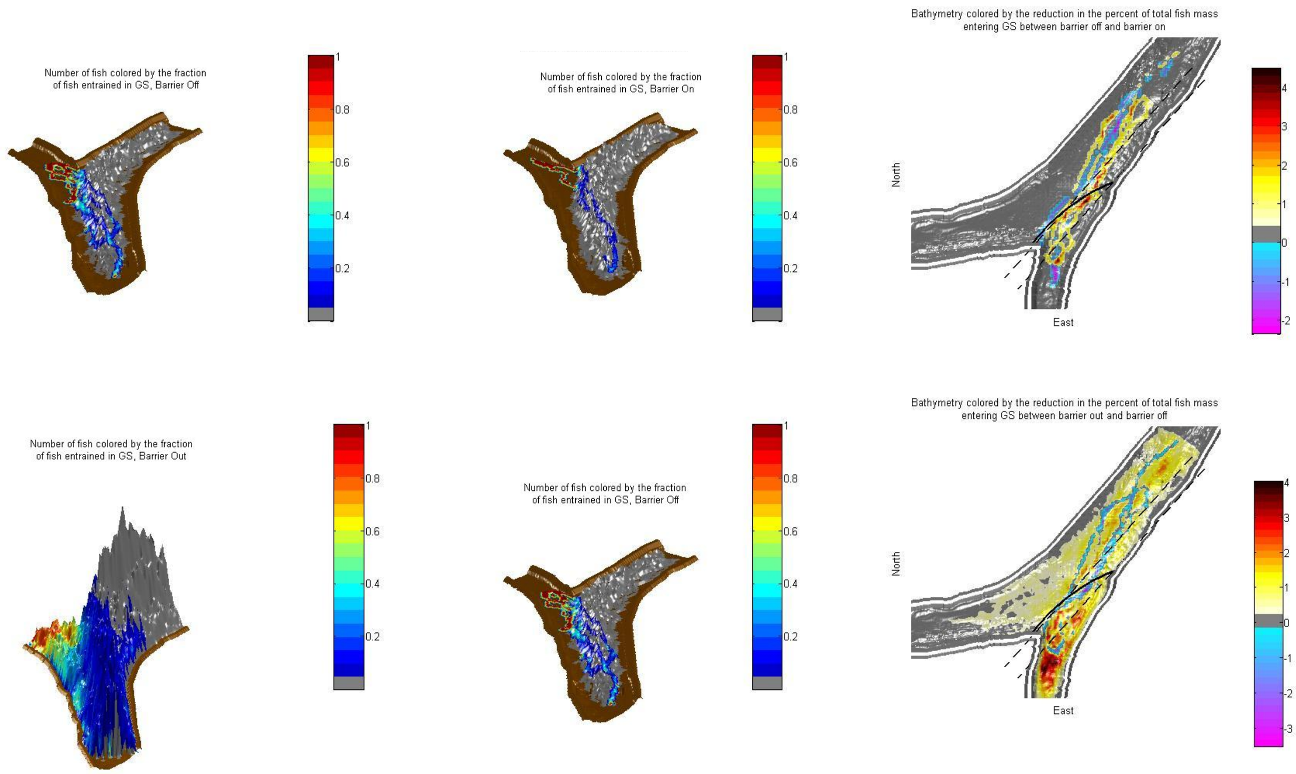
- When the BAFF was turned on, entrainment rates in the Sacramento River upstream of the barrier were reduced, the spatial gradient in the entrainment rate in the cross-stream direction was increased, and the location of the point in the river cross-section where entrainment transitioned from greater than 50 percent to less than 50 percent (shown in green) shifted in the river-left direction. Although the distance of this shift was relatively small, it occurred where the gradients in fish density were high, so the total effect on entrainment was significant;

- BAFF operations caused a much larger reduction in the total number of fish entering Georgiana Slough in the area immediately upstream of the region where the critical streakline passed over the barrier than in any other portion of the junction. This is likely due to the fact that fish in this area only have to move a small distance to avoid being entrained in Georgiana Slough, so small changes in a fish's position can affect entrainment in this area; and

- Barrier operations did not significantly decrease entrainment rates or overall entrainment on the far river-left edge of the Sacramento River upstream of the barrier. This could be due to the fact that fish in this area have to move a significant distance in the cross stream direction (25 to 40 m) to avoid being entrained in Georgiana Slough. The high downstream velocities that were common when the barrier was installed could have made it difficult for small fish to make a lateral movement of this magnitude before being advected over the top of the barrier.

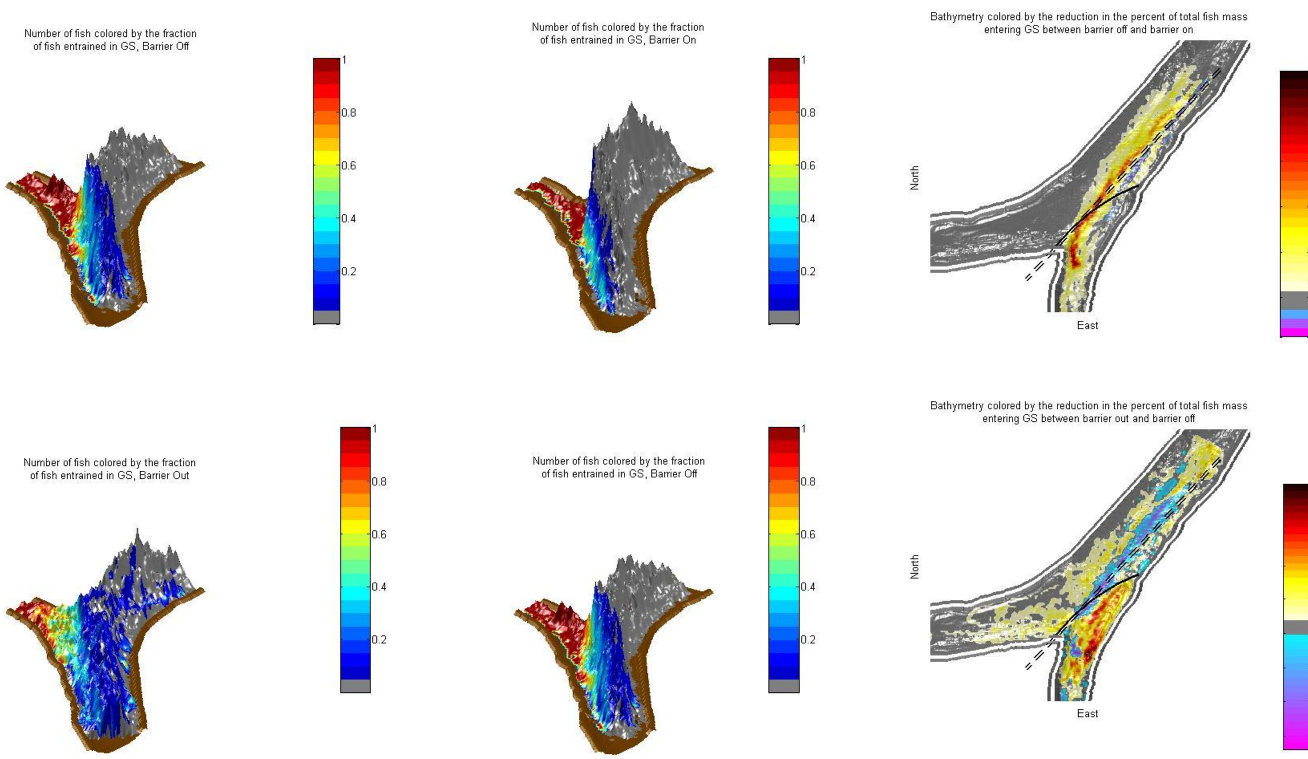
- Comparisons between periods when the barrier was installed and off, and periods when the barrier was not installed suggest that total entrainment in Georgiana Slough increased significantly in the area immediately upstream of the region where the critical streakline passed over the barrier, this being due to the fact that entrainment rates were higher in this area when the barrier was installed than when the barrier was out. The fact that this effect was consistent across all velocity conditions where data were collected suggests that the physical footprint of the barrier has a real effect and was not an artifact of differences in other covariates between study groups.

The observed increase in entrainment in areas upstream of the barrier when it is turned off relative to periods when it is not installed has important implications for the design of future barriers and guidance structures, because it suggests that fish that pass over the barrier in the region around the critical streakline are responding to the barrier's presence when it is off, but that this response occurs after fish have moved over the barrier. This concept is illustrated in **Figure 3.5-26**.



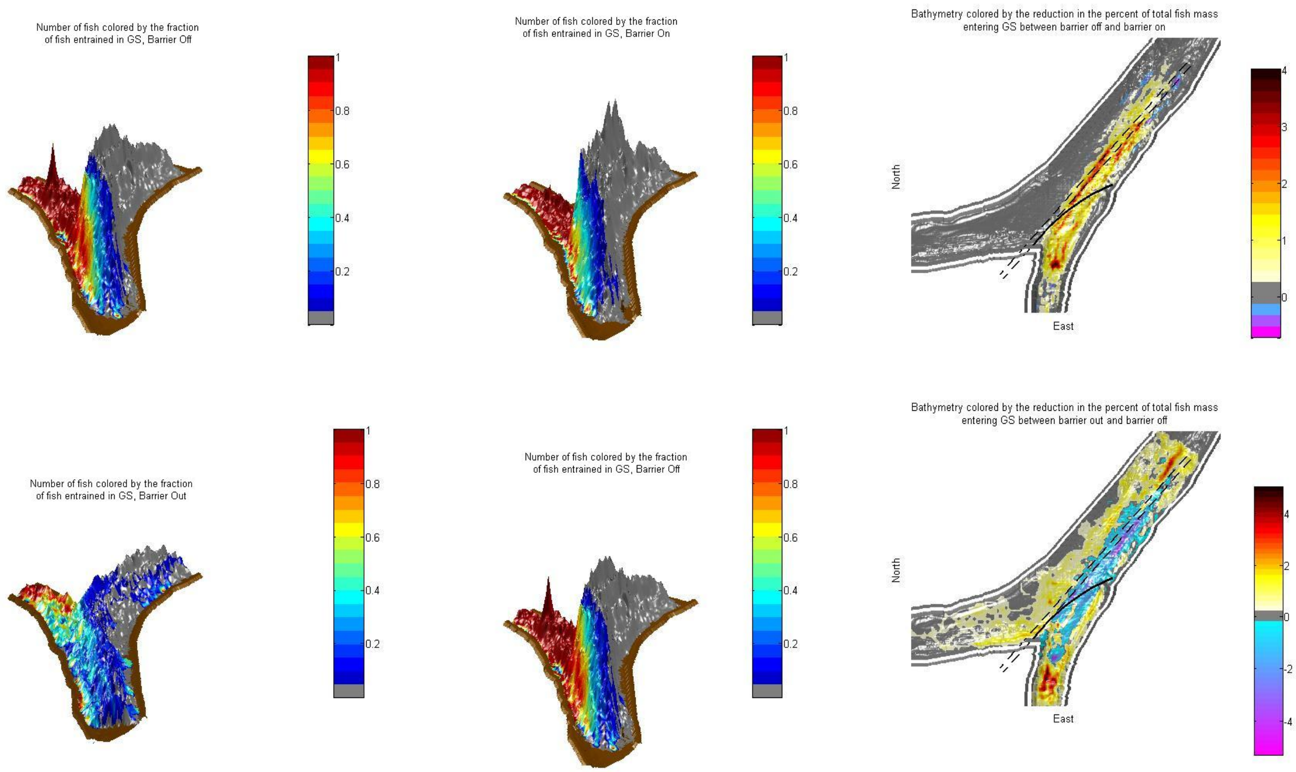
Notes: Figure illustrating the effects of barrier operations and barrier installation on the spatial distribution of fish mass and Georgiana Slough entrainment in the junction area. The upper row compares the spatial distribution of several metrics with the barrier installed and off, and barrier installed and on. The bottom row compares the spatial distribution of several metrics with the barrier not installed, and the barrier installed and off. In the first two columns of figures the bathymetry is represented by the brown surface, and the distribution of all fish in the junction area is indicated by the height of the surface above the bathymetry. The fish distribution surface is colored by the Georgiana Slough entrainment rate, areas where Georgiana Slough entrainment are equal to zero are colored grey. The two plots in the right hand column show the spatial distribution of the reduction in the number of fish entering Georgiana Slough between the condition in column two (Barrier On, or Barrier Installed), and the condition in column one (Barrier Off, or Barrier Out). The reduction in the number of fish entering Georgiana Slough is expressed as the percent in the total number of fish that entered the junction for each condition in order to account for sample size differences between each case. A positive reduction value indicates that the condition in column two reduced entrainment in Georgiana Slough relative to the condition in column one, a negative reduction value indicates that the condition in column two increased entrainment in Georgiana Slough relative to the condition in column one. In the two plots on the right hand column, the location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for the covariate period illustrated are shown as dotted black lines.

Figure 3.5-22 **Illustration of Barrier Effects during Ebb1 Velocity Conditions (Downstream Critical Streakline Ranging from -37.5m to -5m)**



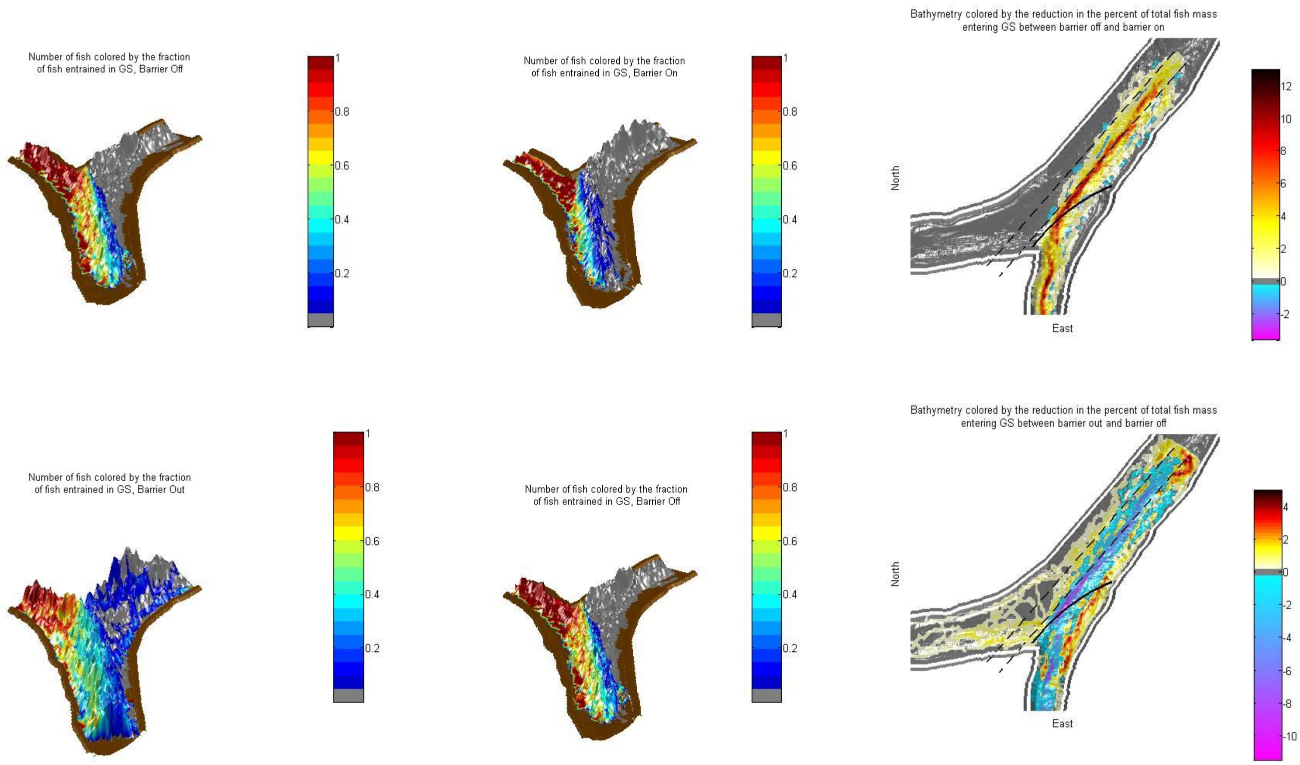
Notes: Figure illustrating the effects of barrier operations and barrier installation on the spatial distribution of fish mass and Georgiana Slough entrainment in the junction area. The upper row compares the spatial distribution of several metrics with the barrier installed and off, and barrier installed and on. The bottom row compares the spatial distribution of several metrics with the barrier not installed, and the barrier installed and off. In the first two columns of figures the bathymetry is represented by the brown surface, and the distribution of all fish in the junction area is indicated by the height of the surface above the bathymetry. The fish distribution surface is colored by the Georgiana Slough entrainment rate, areas where Georgiana Slough entrainment are equal to zero are colored grey. The two plots in the right hand column show the spatial distribution of the reduction in the number of fish entering Georgiana Slough between the condition in column two (Barrier On, or Barrier Installed), and the condition in column one (Barrier Off, or Barrier Out). The reduction in the number of fish entering Georgiana Slough is expressed as the percent in the total number of fish that entered the junction for each condition in order to account for sample size differences between each case. A positive reduction value indicates that the condition in column two reduced entrainment in Georgiana Slough relative to the condition in column one, a negative reduction value indicates that the condition in column two increased entrainment in Georgiana Slough relative to the condition in column one. In the two plots on the right hand column, the location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for the covariate period illustrated are shown as dotted black lines.

Figure 3.5-23 **Illustration of Barrier Effects during Ebb2 Velocity Conditions (Downstream Critical Streakline Ranging from -5m to 0.0m)**



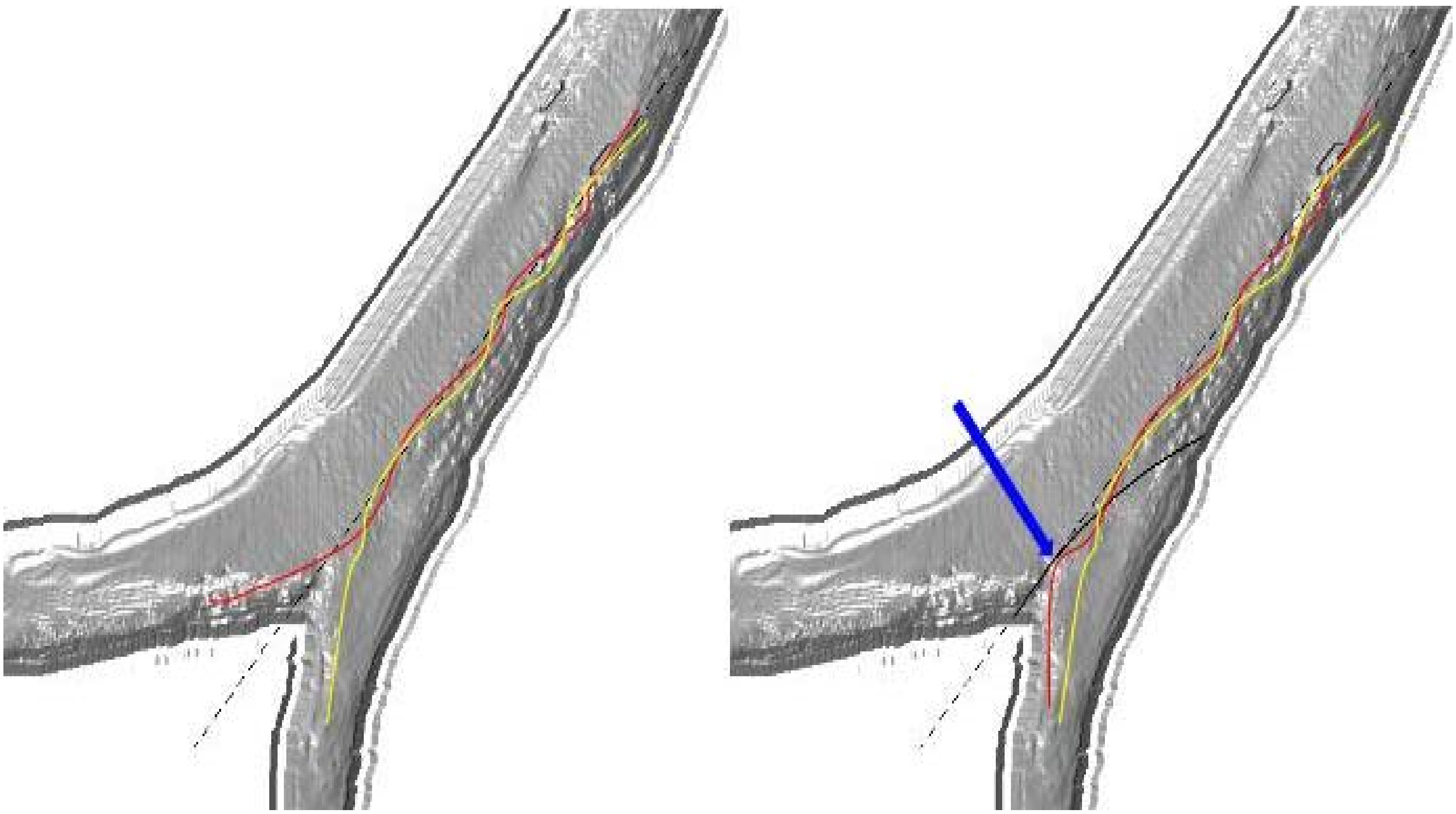
Notes: Figure illustrating the effects of barrier operations and barrier installation on the spatial distribution of fish mass and Georgiana Slough entrainment in the junction area. The upper row compares the spatial distribution of several metrics with the barrier installed and off, and barrier installed and on. The bottom row compares the spatial distribution of several metrics with the barrier not installed, and the barrier installed and off. In the first two columns of figures the bathymetry is represented by the brown surface, and the distribution of all fish in the junction area is indicated by the height of the surface above the bathymetry. The fish distribution surface is colored by the Georgiana Slough entrainment rate, areas where Georgiana Slough entrainment are equal to zero are colored grey. The two plots in the right hand column show the spatial distribution of the reduction in the number of fish entering Georgiana Slough between the condition in column two (Barrier On, or Barrier Installed), and the condition in column one (Barrier Off, or Barrier Out). The reduction in the number of fish entering Georgiana Slough is expressed as the percent in the total number of fish that entered the junction for each condition in order to account for sample size differences between each case. A positive reduction value indicates that the condition in column two reduced entrainment in Georgiana Slough relative to the condition in column one, a negative reduction value indicates that the condition in column two increased entrainment in Georgiana Slough relative to the condition in column one. In the two plots on the right hand column, the location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for the covariate period illustrated are shown as dotted black lines.

Figure 3.5-24 **Illustration of Barrier Effects during Ebb3 Velocity Conditions (Downstream Critical Streakline Ranging from 0.0m to +10m)**



Notes: Figure illustrating the effects of barrier operations and barrier installation on the spatial distribution of fish mass and Georgiana Slough entrainment in the junction area. The upper row compares the spatial distribution of several metrics with the barrier installed and off, and barrier installed and on. The bottom row compares the spatial distribution of several metrics with the barrier not installed, and the barrier installed and off. In the first two columns of figures the bathymetry is represented by the brown surface, and the distribution of all fish in the junction area is indicated by the height of the surface above the bathymetry. The fish distribution surface is colored by the Georgiana Slough entrainment rate, areas where Georgiana Slough entrainment are equal to zero are colored grey. The two plots in the right hand column show the spatial distribution of the reduction in the number of fish entering Georgiana Slough between the condition in column two (Barrier On, or Barrier Installed), and the condition in column one (Barrier Off, or Barrier Out). The reduction in the number of fish entering Georgiana Slough is expressed as the percent in the total number of fish that entered the junction for each condition in order to account for sample size differences between each case. A positive reduction value indicates that the condition in column two reduced entrainment in Georgiana Slough relative to the condition in column one, a negative reduction value indicates that the condition in column two increased entrainment in Georgiana Slough relative to the condition in column one. In the two plots on the right hand column, the location of the BAFF is shown as a solid black line, and the location of the minimum and maximum downstream critical streakline locations for the covariate period illustrated are shown as dotted black lines.

Figure 3.5-25 **Illustration of Barrier Effects during Ebb4 Velocity Conditions (Downstream Critical Streakline ranging from +10m to +40m)**



Notes: Conceptual illustration showing the path of two hypothetical fish with the barrier out and the barrier installed. In the plot on the left, the fish are advected along the critical streakline and split with the water velocity at the gore point. In the plot on the right the red fish senses the shear signature of the barrier after it passes above it at the point illustrated by the blue arrow, and swims to avoid being advected into the barrier's turbulence plume.

Figure 3.5-26 **Conceptual Illustration Showing how Barrier-Induced Turbulence could Increase Entrainment Between Periods when the Barrier is Out and the Barrier is Installed and Off**

EFFECTS OF LIGHT ON BARRIER OPERATIONS

In order to explore the differences in barrier operations during light and dark conditions, plots were made to explicitly highlight the differences between the spatial distribution of fish density and entrainment rates for fish exposed to barrier operations during light and dark conditions (**Figure 3.5-27**). In order to verify that any observed differences were due to barrier operations and not some other factor, the same plots were developed to compare the same distributions between light and dark conditions when the barrier was turned off (**Figure 3.5-28**). These figures illustrate the following points:

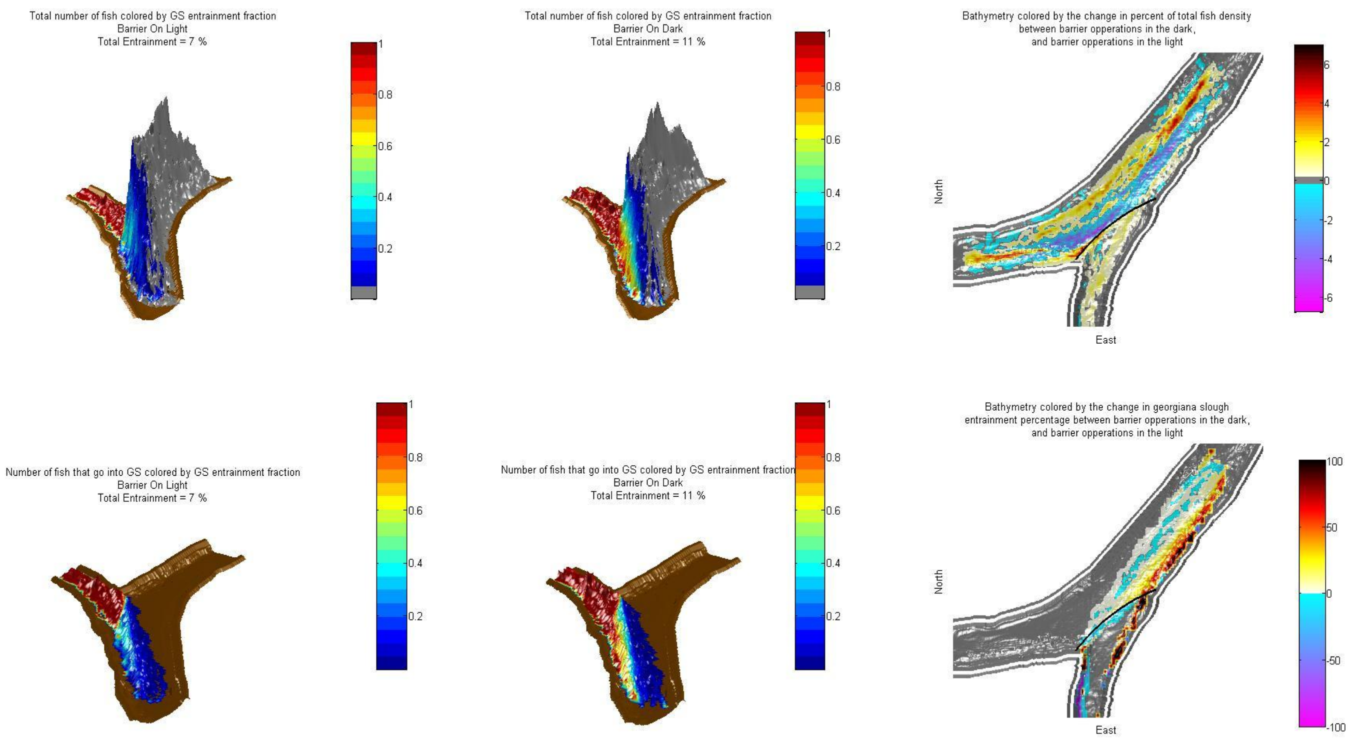
- During dark periods when the barrier was on, the distribution of fish density in the junction area shifted to river right (away from the barrier) relative to the distribution of fish for periods when the barrier was on in the light. The distributions of fish density for periods when the barrier was off show a slight shift in the opposite direction, which suggests that the shift observed during barrier operations is due to the barrier and not to other covariates that change with light; and

- During periods when the barrier is on in the dark the rate of entrainment near the left bank of the Sacramento River increases significantly, but entrainment rates in the rest of the Sacramento River change only slightly. Again, this effect is not seen in the distribution of differences between light and dark periods when the barrier was off, so the effect is likely due to the barrier and not other covariates that change with light.

The net result of these two effects is that overall entrainment is slightly higher during periods when the barrier is on at night versus periods when the barrier is on during the day. However, the magnitude of the difference in the overall entrainment rate is relatively small because these two effects act to cancel each other out; entrainment is higher near the left bank of the Sacramento River during barrier operations in the dark, but barrier operations in the dark shift fish away from this area. If barrier operations during dark periods produced only one of these effects relative to barrier operations during light periods then the observed difference in overall entrainment rates would be greater.

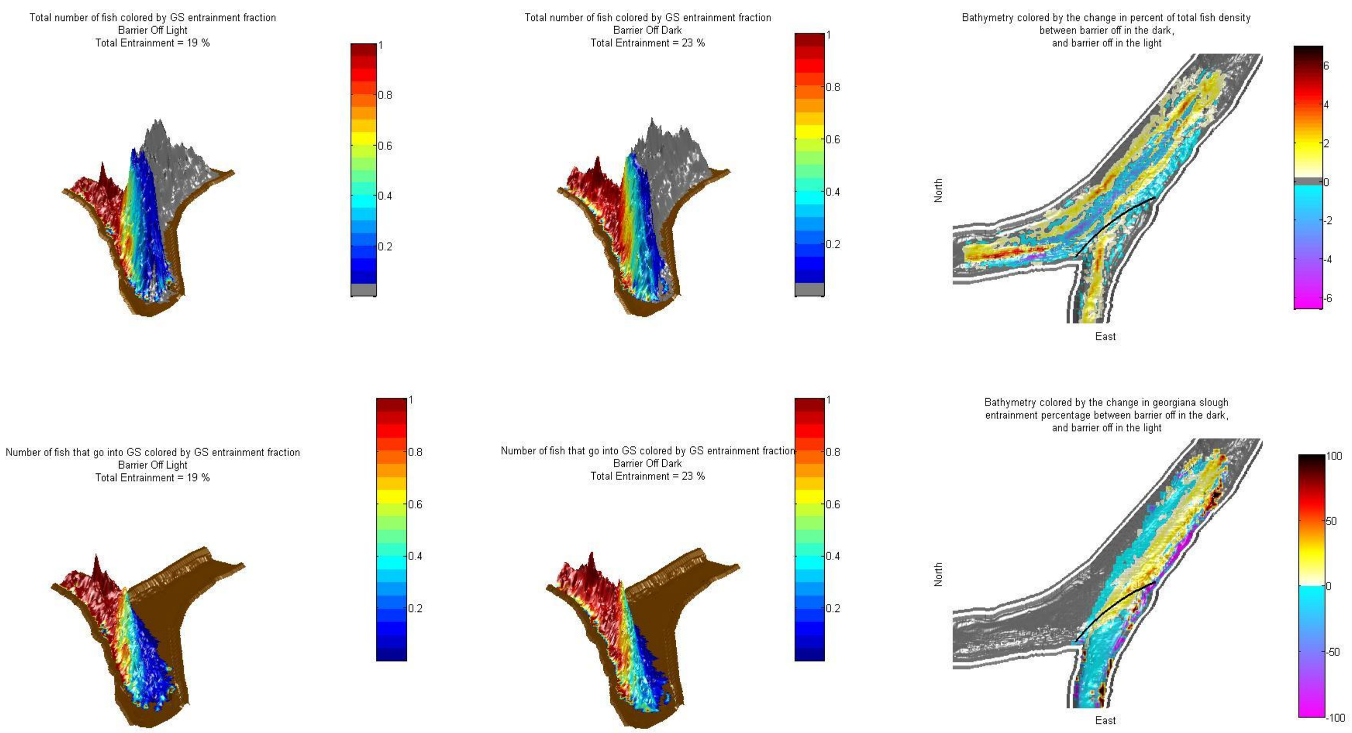
The overall entrainment rates for fish passing through the junction when the BAFF was off was also slightly higher during dark periods than during light periods, but this trend was due to a different mechanism than the change observed when the BAFF was on. The distribution of fish passing through the junction area at night when the barrier was off was shifted slightly to the left of the distribution of fish passing through the junction area when the barrier was off during the day, and consequently, more fish passed through areas with higher Georgiana Slough entrainment rates when the barrier was off at night. It is possible that the day/night shift in the observed fish density distributions for periods when the barrier was off was not caused by fish responding to the barrier, but rather, was due to unmeasured covariates that changed with light.

This page intentionally left blank.



Notes: Figure illustrating the different effects of barrier operations at night during light and dark periods. The first two columns in the top row show the total fish distribution surface colored by the Georgiana Slough entrainment rate, areas where Georgiana Slough entrainment are equal to zero are colored grey. The first two columns in the bottom row show the number of fish that enter Georgiana Slough in each region in the junction, colored by the Georgiana Slough entrainment rate. The plot on the top right shows the change in total fish density between times when the barrier was on in the dark, and times when the barrier was on in the light. Positive change numbers indicate that more fish were in a grid cell during the dark than during the light. Negative change numbers indicate that the fewer fish were present in the dark than in the light. The plot on the bottom right shows the change in the Georgiana Slough entrainment percentage between times when the barrier was on in the dark, and times when the barrier was on in the light. Positive change numbers indicate that a higher percentage of the fish in each grid cell were entrained in Georgiana Slough during the dark than during the light. Negative change numbers indicate that a lower percentage of the fish in each grid cell were entrained in Georgiana Slough in the dark than in the light. Note that the entrainment rate is expressed as the entrainment percentage (entrainment rate X 100%) for display purposes. The location of the barrier is shown as a solid black line.

Figure 3.5-27 **Illustration of Differences between Spatial Metrics with the Barrier On During Dark and Light Conditions**



Notes: Figure illustrating the different effects of barrier, when it is turned off, at night during light and dark periods. The first two columns in the top row show the total fish distribution surface colored by the Georgiana Slough entrainment rate, areas where Georgiana Slough entrainment are equal to zero are colored grey. The first two columns in the bottom row show the number of fish that enter Georgiana Slough in each region in the junction, colored by the Georgiana Slough entrainment rate. The plot on the top right shows the change in total fish density between times when the barrier was off in the dark, and times when the barrier was off in the light. Positive change numbers indicate that more fish were in a grid cell during the dark than during the light. Negative change numbers indicate that the fewer fish were present in the dark than in the light. The plot on the bottom right shows the change in the Georgiana Sough entrainment percentage between times when the barrier was off in the dark, and times when the barrier was off in the light. Positive change numbers indicate that a higher percentage of the fish in each grid cell were entrained in Georgiana Slough during the dark than during the light. Negative change numbers indicate that a lower percentage of the fish in each grid cell were entrained in Georgiana Slough in the dark than in the light. Note that the entrainment rate is expressed as the entrainment percentage (entrainment rate X 100%) for display purposes. The location of the barrier is shown as a solid black line.

Figure 3.5-28 **Illustration of Differences between Spatial Metrics with the Barrier Off During Dark and Light Conditions**

SUMMARY OF KEY FINDINGS

The arrival time distribution for fish released during the North Delta Study showed that these fish were much less likely to move during dark periods than fish released during the 2011 and 2012 GSNPB studies. It is likely that this difference is partially due to the different release points used for the North Delta Study and the GSNPB studies – transit from the GSNPB release site in the Sacramento River downstream of Steamboat Slough to the study site at the Sacramento River/Georgiana Slough divergence was on the order of several hours compared to several days for fish released near the City of Sacramento. Hatchery-reared study fish released at the City of Sacramento had several days to adjust from hatchery conditions to a natural river environment and several day/night cycles with which to adjust their diurnal behavioral patterns.

All but one of the 2012 GSNPB Study fish that passed through the junction during converging, reversing, and slack conditions were classified as predators. Additionally, most of the 2012 GSNPB Study fish that passed through the junction during ebb tides when the downstream critical streakline time series was greater than +20 m were also classified as predators. It is impossible to know if these fish were in fact predators, or juvenile Chinook salmon moving through the junction during times when tidal forcing created complex velocity structures and/or behavioral patterns, but this finding should be considered when designing future studies.

Periods of reversing flow, converging flow, and ebb periods when the downstream critical streakline time series was greater than +10 m accounted for over 50 percent of the total entrainment in Georgiana Slough during the North Delta Study. The 2011 and 2012 GSNPB studies provide little to no information on the effects of the barrier under these water velocity conditions.

Total fish mass was not uniformly distributed in the river cross-section for any covariate group, and fish entrained in Georgiana Slough were only uniformly distributed in the river cross-section during slack periods. This means that the entrainment of outmigrants is dependent on velocity patterns in the junction, and that the percentage of fish entrained in Georgiana Slough is not identically equal to the percentage of water entrained in Georgiana Slough.

For North Delta Study fish during dark periods, the distribution of fish for each fate changed significantly over the range of tidal velocity patterns, and these changes coincided with the changes in location of the critical streakline for both flood and ebb conditions.

For North Delta Study fish moving during dark periods, the point in the river cross-section where entrainment in Georgiana Slough dropped below 50 percent was located very close to the lower critical streakline boundary for each ebb tide covariate group. This observation supports the use of flow ratios and critical streakline values to estimate effects of velocity patterns on juvenile entrainment in river junctions.

When the BAFF was turned on, entrainment rates in the Sacramento River upstream of the barrier were reduced, the spatial gradient in the entrainment rate in the cross stream direction was increased, and the location of the point in the river cross-section where entrainment transitioned from greater than 50 percent to less than 50 percent shifted to the river-left direction. Although this shift was relatively small, it occurred where spatial gradients in fish density were high, so the total reduction in entrainment was significant.

Barrier operations caused a much larger reduction in the total number of fish entering Georgiana Slough in the area immediately upstream of the region where the critical streakline passed over the BAFF than in any other portion of the junction. This is likely due to the fact that fish in this area only have to move a small distance to avoid being entrained in Georgiana Slough.

Comparisons between periods when the BAFF was installed and off, and periods when the BAFF was not installed suggest that the presence of the barrier when it was turned off increased entrainment in Georgiana Slough significantly in the area immediately upstream of the region where the critical streakline passed over the barrier.

There were significant differences between the spatial distribution of Georgiana Slough entrainment rates and the spatial distribution of fish density calculated for periods when the barrier was on under dark conditions and for periods when the barrier was on under light conditions. It is likely that these differences are due to differences in the way that fish respond to the barrier during light and dark conditions.

3.6 GENERALIZED LINEAR MODELING OF TAGGED FISH FATES

Results of the first two years of the HOR study suggested that variables not included in the hypothesis-testing framework described previously (see Sections 2.2, 2.3, and 3.2) may influence barrier effectiveness (Bowen et al. 2012; Bowen and Bark 2012. To examine the influence of these variables, an analysis was conducted to predict the probability that a tagged Chinook salmon would remain in the Sacramento River rather than be entrained into Georgiana Slough. Ultimately, this analysis was directed toward answering the following question: After accounting for other variables, does the operation of the BAFF significantly decrease the probability that a tagged fish would become entrained into Georgiana Slough? The analysis involved using a GLM with a binomial distribution and logit link function, similar to the technique used by Perry (2010), to predict entrainment probability into Georgiana Slough from the Sacramento River. This analysis technique was used previously to assess the data from the 2011 GSNPB Study (DWR 2012; Perry et al. 2012).

In addition to fish released explicitly for the study, fish were also released by the SRCSD and included in the analysis. Fish moved through the study area when the BAFF was on, off, in the process of being removed, and after it was completely removed. This presented the opportunity to examine the influence of BAFF effectiveness under different variables when the BAFF was on, off, and when it was no longer in place. This portion of the analysis is presented in **Appendix H**.

3.6.1 METHODS

For this part of the analysis, the fate of each fish (F_i) was modeled as a Bernoulli random variable where $F_i = 1$ represented fish entering Georgiana Slough and $F_i = 0$ represented fish remaining in the Sacramento River. Migration routes used by each fish were determined based on whether 2D tracks exited the array via the Sacramento River or Georgiana Slough. The probability of entrainment into Georgiana Slough($\pi_{G,i}$) was modeled as a function of individual covariates using generalized linear models in the R statistical platform (R Development Core Team 2011). The logit link function, which models ln($\pi_{G,i}$ /(1-$\pi_{G,i}$) as a linear function of covariates, was used. Entrainment probability for each individual was then expressed as a function of covariates using the inverse logit function:

$$\pi_{G,i} = \frac{\exp\left(\beta_0 + \beta_1 Y_{1,i}, \cdots, \beta_n Y_{n,i}\right)}{1 + \exp\left(\beta_0 + \beta_1 Y_{1,i}, \cdots, \beta_n Y_{n,i}\right)}$$

where: $Y_{1,i}$, …, $Y_{n,i}$ are the values of n covariates for the ith fish, β_0 is the intercept, and β_1, …, β_n are slope coefficients for the n covariates.

For the 2012 GSNPB Study, six covariates were considered for inclusion in candidate models:

- operation of the BAFF (B; on = 1, off = 0);
- time of day (D; day =1, night = 0);
- discharge entering the river junction (Q, cfs·[1,000][4]);
- cross-stream position (X), which is the location of tagged fish in the channel cross-section;
- the location of the critical streakline in the channel cross-section (S); and
- the along-stream location (A) of the fish in the along-river axis in relation to the most upstream point of the study area.

The upstream extent of the study area was defined as 157 m upstream from the most upstream point of the BAFF. Although most fish were detected at the entrance to the study area, some were not detected until well inside the study area; therefore, the along-stream location (A) was included in the analysis to examine whether location in the y dimension had an effect on entrainment.

The cross-stream position of each fish was measured using the 2D position nearest to a cross-section aligned 157 m upstream from the most upstream point of the BAFF (**Figures 2-2** and **2-5**) (see also Section 3.4). All other individual covariates were based on the time when fish entered the study area. The critical streakline estimates the cross-stream location that divides the river channel into water parcels entering either Georgiana Slough or the Sacramento River:

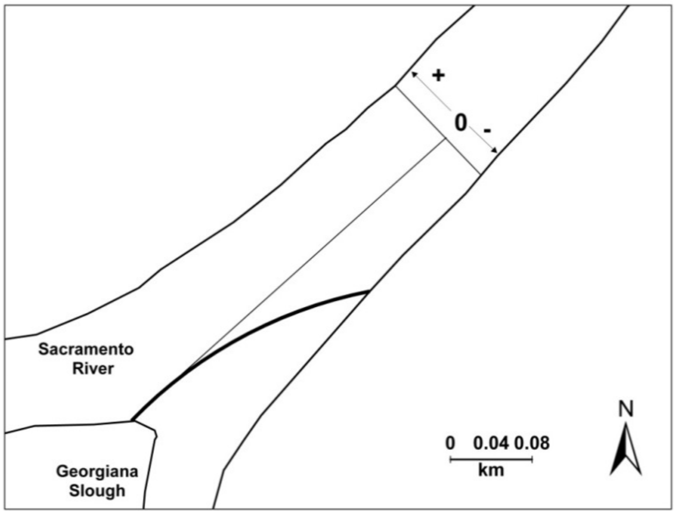
$$S = W\left(\frac{Q_G}{Q_S + Q_G}\right) - 37.5$$

where:

W is the width of the channel (100 m) and Q_G and Q_S are discharge of Georgiana Slough and the Sacramento River, respectively, measured downstream from the river junction.

This equation makes the simplifying assumption of a rectangular channel and uniform velocity distribution. Both S and X were offset by 37.5 m to set the origin to the outermost position of the BAFF (**Figure 3.6-1**). Thus, for $X < 0$, fish were located on the Georgiana Slough side of the BAFF in the river channel just upstream from the junction, and for $X > 0$, fish were located on the Sacramento River side of the BAFF in the river channel just upstream from the junction. Likewise, for $S < 0$, the critical streakline intersects the BAFF, but for $S > 0$ the streakline extends into the Sacramento River beyond the BAFF. Similarly, $X < S$ indicates that fish were located in the parcel of water likely to enter Georgiana Slough, whereas $X > S$ indicates that fish were more likely to remain in the Sacramento River.

[4] While not explicitly used as covariates, temperature and turbidity typically co-vary with flow (Q) and, therefore, flow can be considered a surrogate for these parameters. Water velocity can also co-vary with flow; however, it is also strongly influenced by tide phase.



Note:
The heavy solid line shows the location of the BAFF in the river junction and thin lines show the streamwise (parallel to mean velocity vectors) and cross-stream (perpendicular to mean velocity vectors) coordinate system. Zero indicates the origin with positive cross-stream coordinates indicating locations to the Sacramento River side of the BAFF and negative cross-stream coordinates to the Georgiana Slough side of the BAFF.

Figure 3.6-1 Streamwise and Cross-Stream Coordinate System in Relation to the Sacramento River and Georgiana Slough

The model selection process consisted of fitting alternative models to the data, ranking the models based on an information criterion, and then using the best-fit model for inference. The Bayesian Information Criterion (BIC) was used for model selection because BIC tends to be more conservative (i.e., selects simpler models) than other model selection criteria (e.g., Likelihood Ratio Test or Akaike's Information Criterion [AIC]) when sample size is relatively large (Ward 2008). Use of either AIC or BIC seeks to identify the most parsimonious model by trading goodness of fit, measured by the maximized log-likelihood of a given model, for a penalty term based on the number of parameters used to fit the model. These information criteria differ only in the penalty term for the number of parameters. For AIC, the penalty term is 2k, and for BIC, the penalty term is $k \cdot \ln(n)$, where k is the number of parameters and n is the sample size. Models with lower BIC are considered more parsimonious models. Differences of < 3 BIC units were interpreted between models (ΔBIC) as models that explain the data equally well.

To identify the best models for juvenile Chinook salmon and steelhead, a series of main-effects models were fit, and two-way interactions (i.e., products of variables) were added to the best-fit main effects model. All main-effects models formed were fit using the six predictor variables, resulting in 66 models. Biologically reasonable two-way interactions were then added to the main-effects model that was selected on the basis of BIC differences among models. Interaction terms assessed whether the effectiveness of the BAFF varied with time of day (*D*), cross-stream location of fish (*X*), and discharge (*Q*). The model with the lowest BIC value in the set of models was then selected as the best-fit model for explaining variation in migration routing of juvenile salmonids. To assess the relative importance of each variable, the difference in BIC of each model (ΔBIC) relative to lowest-BIC model was calculated within groups of models of similar complexity. Models were loosely grouped according to the number of variables in each model.

Model fit was assessed according to the data using both quantitative and descriptive techniques. To check for systematic deviations between predicted values and observed values, the Hosmer-Lemeshow goodness-of-fit test was performed (Hosmer and Lemeshow 2000). The area under the receiver operating curve (AUC) was also calculated to quantify how well the model predicts the fates of fish (Hosmer and Lemeshow 2000). The AUC is calculated as follows: If estimated probabilities of $\pi_{G,i}$ are greater than an arbitrary cutoff value of π_G, then the *i*th fish is assigned to Georgiana Slough. For a particular cutoff value, the actual route used by each fish is compared to the predicted route, and the false-positive and true-positive rate is calculated. The receiver operating curve (ROC) plots the true-positive rate versus the false-positive rate for all possible cutoff values, and the AUC is the area under this curve. An AUC of 0.5 indicates that the model has no ability to predict the fish's migration route, whereas an AUC of 1 indicates perfect classification ability. In practice, models with an AUC between 0.8 and 0.9 are considered to have "excellent" discrimination ability, and an AUC greater than 0.9 is considered "outstanding" (Hosmer and Lemeshow 2000).

Results from the best-fit model run were presented in two ways. The parameter estimates (i.e., the slope coefficients) indicate whether each variable positively or negatively influenced entrainment into Georgiana Slough. To illustrate the effect of each variable on entrainment probability, the relationship between $\pi_{G,i}$ and each covariate was plotted while all other covariates were held constant. In addition, the observed fraction of fish entrained into Georgiana Slough arises as a function of individual entrainment probabilities integrated across the conditions experienced by each fish as it passed through the river junction. To illustrate the effect of the BAFF under different hydrodynamic conditions, the best-fit model was used to predict probabilities of entrainment for the complete time series of 15-minute hydrodynamic data during the study period. For this analysis, entrainment was predicted by assuming that the BAFF had been turned off during the entire study period and that the BAFF had been operating for the entire study period. This approach allowed the predicted effect of the BAFF to be examined over the full range of hydrodynamic conditions observed during the study.

3.6.2 Results and Discussion

River Conditions and BAFF Operation

During the study, between March 6 and April 29, 2012, river flow entering the river junction at Georgiana Slough peaked on March 18 at about 30,000 cfs. After the peak-flow event, flow oscillated between approximately 20,000 cfs and 10,000 cfs weekly for the remainder of the study (**Figure 3.6-2**).

Of the 1,501 Chinook salmon released, 350 fish were excluded from this analysis because of mortality upstream from the river junction or because they were classified as eaten within the array, resulting in 1,151 Chinook salmon available for analysis. Of the 299 steelhead released, 69 were excluded from this analysis because of mortality upstream from the river junction or because they were classified as eaten within the array, resulting in 106 steelhead available for analysis.

Overall, 11.4 percent of the Chinook salmon available for analysis were entrained into Georgiana Slough when the BAFF was on, and 24.1 percent of the Chinook salmon entered Georgiana Slough when the BAFF was off. Steelhead followed a similar pattern: 10.5 percent of the steelhead available for analysis entered Georgiana Slough when the BAFF was on, and 23.4 percent of the steelhead entered Georgiana Slough when the BAFF was off.

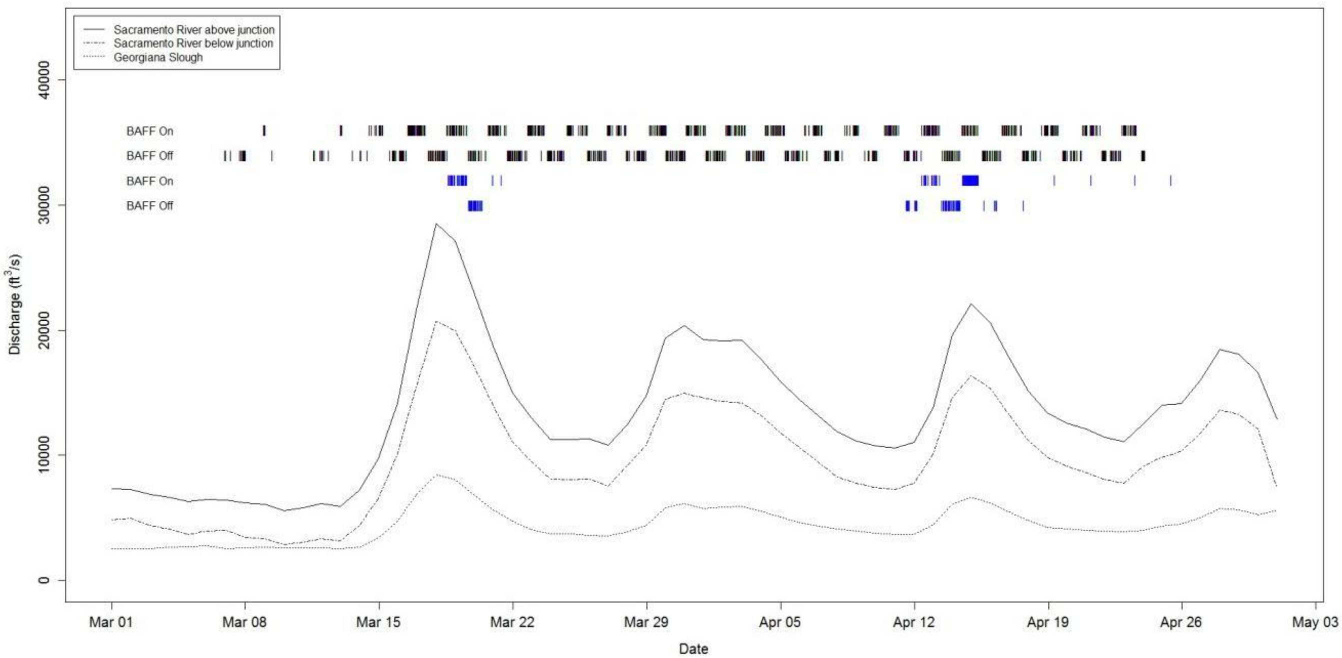


Figure 3.6-2 **River Discharge and BAFF Treatment at Time of Detection in the Array for Juvenile Chinook Salmon (Black Marks) and Steelhead (Blue Marks)**

MODEL SELECTION RESULTS FOR CHINOOK SALMON

Model selection results for Chinook salmon suggested that cross-stream position (*X*), followed by streakline (*S*) and BAFF operation (*B*), had the largest influence on entrainment into Georgiana Slough but that all variables affected migration routing to some extent. Among single-variable models, cross-stream location of fish (*X*) had the lowest BIC value, followed by streakline (*S*), BAFF operation (*B*), river discharge (*Q*), time of day (*D*), and along-stream location (*A)* (**Table 3.6-1**). Among two-variable models, the lowest BIC model included both *X, S,* and *B*, supporting the hypothesis that the BAFF affected migration routing (**Table 3.6-1**). For the more complex models, the BIC rankings followed the ranking of simpler models. For example, among three-variable models, *X* appeared in the top eleven models and *B* appeared in the top model. Among all main-effects models, the model with the lowest BIC value included *X*, *B*, *Q*, and *S* (**Table 3.6-1**).

Table 3.6-1
Model Selection Results for Logistic Regression Expressing the Probability of Juvenile Chinook Salmon Entering Georgiana Slough as a Function of Covariates

Model	Group	Number of Variables	NLL	BIC	Group ∆BIC	Overall ∆BIC
$B + S + Q + X + Q * X$	1	5	428.21	898.72	0	0
$B + S + Q + X + B * Q$	1	5	437.88	918.05	19.34	19.33
$B + S + Q + X + D + D * X$	1	6	436.22	921.79	23.07	23.07
$B + S + Q + X + A + A * B$	1	6	437.42	924.18	25.46	25.46
$B + S + Q + X + B * X$	1	5	442.01	926.3	27.59	27.58
$B + S + Q + X + D + D * B$	1	6	440.86	931.06	32.34	32.34
$B + S + Q + X + D + A$	2	6	439.14	927.63	0	28.91

Table 3.6-1
Model Selection Results for Logistic Regression Expressing the Probability of Juvenile Chinook Salmon Entering Georgiana Slough as a Function of Covariates

Model	Group	Number of Variables	NLL	BIC	Group ΔBIC	Overall ΔBIC
$B + S + Q + X + A$	3	5	440.47	923.24	0	24.52
$B + S + Q + X + D$	3	5	441.29	924.88	1.64	26.16
$B + S + X + D + A$	3	5	451.79	945.88	22.64	47.16
$S + Q + X + D + A$	3	5	455.59	953.47	30.24	54.75
$B + Q + X + D + A$	3	5	464.85	971.99	48.75	73.27
$B + S + Q + D + A$	3	5	488.06	1018.41	95.17	119.69
$B + S + Q + X$	4	4	442.71	920.66	0	21.94
$B + S + X + A$	4	4	452.58	940.4	19.74	41.68
$B + S + X + D$	4	4	453.67	942.58	21.92	43.86
$S + Q + X + D$	4	4	457.14	949.52	28.87	50.8
$S + Q + X + A$	4	4	457.19	949.62	28.96	50.9
$B + Q + X + D$	4	4	466.62	968.48	47.82	69.76
$B + X + D + A$	4	4	467.52	970.28	49.62	71.56
$S + X + D + A$	4	4	468.36	971.96	51.31	73.24
$B + Q + X + A$	4	4	468.48	972.21	51.56	73.49
$Q + X + D + A$	4	4	480.89	997.01	76.36	98.29
$B + S + Q + A$	4	4	488.63	1012.5	91.84	113.78
$B + S + Q + D$	4	4	490.57	1016.39	95.73	117.67
$B + S + D + A$	4	4	502.81	1040.86	120.2	142.14
$S + Q + D + A$	4	4	504.07	1043.39	122.73	144.67
$B + Q + D + A$	4	4	514.2	1063.64	142.99	164.92
$B + S + X$	5	3	454.51	937.21	0	38.49
$S + Q + X$	5	3	458.78	945.75	8.54	47.03
$B + X + D$	5	3	469.23	966.64	29.43	67.92
$S + X + A$	5	3	469.34	966.88	29.67	68.16
$S + X + D$	5	3	469.69	967.57	30.36	68.85
$B + Q + X$	5	3	470.3	968.79	31.58	70.07
$B + X + A$	5	3	470.35	968.89	31.68	70.17
$Q + X + D$	5	3	482.15	992.5	55.29	93.78
$X + D + A$	5	3	483.9	996	58.79	97.28
$Q + X + A$	5	3	484.91	998.01	60.8	99.29
$B + S + Q$	5	3	491.21	1010.61	73.4	111.89
$B + S + A$	5	3	503.04	1034.28	97.07	135.56
$S + Q + A$	5	3	504.8	1037.79	100.58	139.07
$B + S + D$	5	3	504.85	1037.89	100.68	139.17

Table 3.6-1
Model Selection Results for Logistic Regression Expressing the Probability of Juvenile Chinook Salmon Entering Georgiana Slough as a Function of Covariates

Model	Group	Number of Variables	NLL	BIC	Group ΔBIC	Overall ΔBIC
$S + Q + D$	5	3	506.05	1040.29	103.08	141.57
$B + Q + D$	5	3	516.25	1060.7	123.49	161.98
$B + Q + A$	5	3	516.6	1061.39	124.18	162.67
$B + D + A$	5	3	518.03	1064.26	127.05	165.54
$S + D + A$	5	3	519.07	1066.33	129.12	167.61
$Q + D + A$	5	3	530.4	1088.99	151.78	190.27
$S + X$	6	2	470.7	962.55	0	63.83
$B + X$	6	2	472.11	965.36	2.8	66.64
$X + D$	6	2	485.12	991.38	28.83	92.66
$Q + X$	6	2	486.18	993.5	30.94	94.78
$X + A$	6	2	487.06	995.27	32.72	96.55
$B + S$	6	2	505.11	1031.38	68.82	132.66
$S + Q$	6	2	506.81	1034.76	72.2	136.04
$B + Q$	6	2	518.68	1058.5	95.95	159.78
$S + A$	6	2	519.41	1059.96	97.41	161.24
$B + A$	6	2	519.64	1060.43	97.88	161.71
$B + D$	6	2	519.94	1061.03	98.47	162.31
$S + D$	6	2	520.63	1062.4	99.84	163.68
$Q + D$	6	2	532	1085.15	122.59	186.43
$Q + A$	6	2	533.01	1087.17	124.61	188.45
$D + A$	6	2	534.45	1090.04	127.49	191.32
X	7	1	488.29	990.67	0	91.95
S	7	1	520.98	1056.06	65.39	157.34
B	7	1	521.59	1057.27	66.6	158.55
Q	7	1	534.6	1083.3	92.63	184.58
D	7	1	535.92	1085.94	95.27	187.22
A	7	1	536.25	1086.6	95.93	187.88
Intercept only	7	0	537.72	1082.49	0	183.77

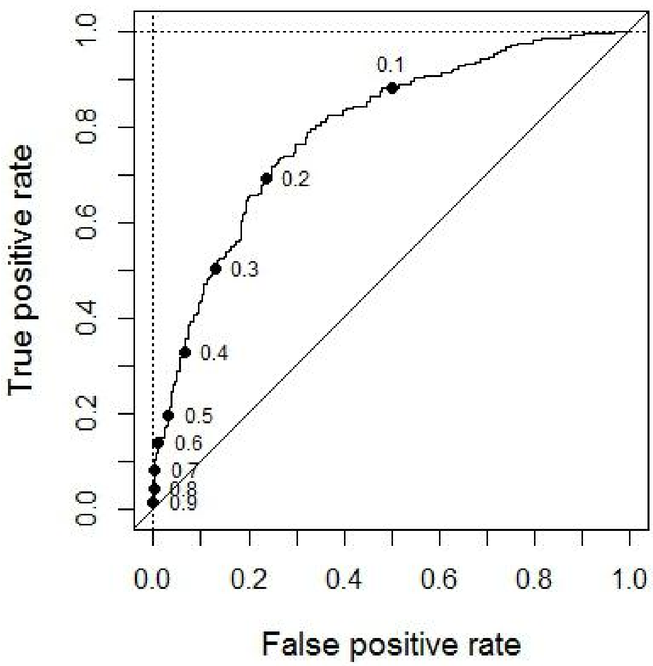
Notes:

NLL = negative log-likelihood; BIC = Bayesian Information Criterion; and ΔBIC is the difference in BIC of each model relative to the lowest BIC model (either in groups of models or over all models).

Among models with interaction terms, a $Q*X$ interaction was strongly supported, having a BIC that was 24.52 units lower than the best-fit main-effects model. Neither a $B*D$ interaction nor a $B*X$ interaction was supported, as evidenced by BIC for these models being larger than the BIC for the four-variable main-effects model

(**Table 3.6-1**). Based on these findings, the model with four covariates and a *Q***X* interaction, which had the lowest BIC over all models, was selected for interference.

Goodness-of-fit diagnostics showed no evidence of lack of fit and indicated that the model predicted the fates of individuals well. The Hosmer-Lemeshow goodness-of-fit test was not significant ($\hat{C}$ = 9.4, df = 17, P = 0.927). The AUC was 0.81, indicating that the model had a good ability to predict fates of individuals. For example, a cutoff of π_G (probability of entering Georgiana slough) > 0.2 correctly predicted 70 percent of the fish that entered Georgiana Slough (true positive rate) and incorrectly assigned only 30 percent of the fish with a Sacramento River fate to Georgiana Slough (**Figure 3.6-3**).

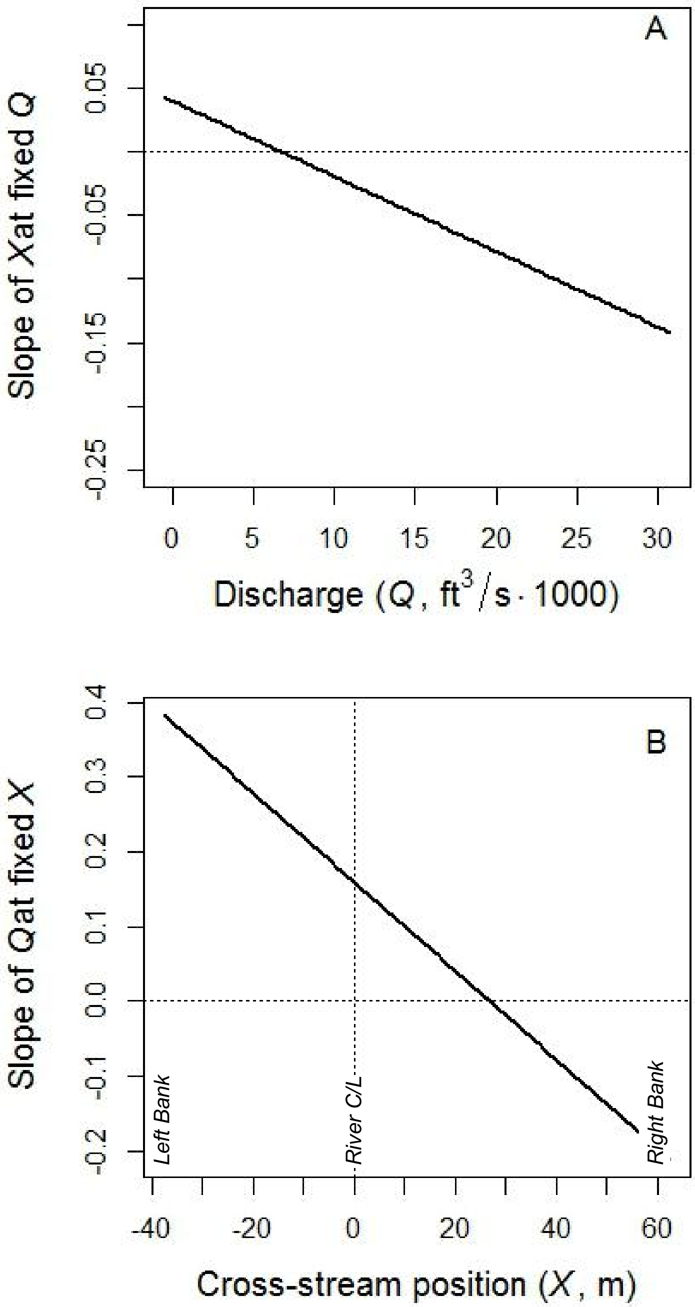


Note:
Results are based on cutoff values of π_G ranging from zero to one (shown as labeled data points). The 45° reference line shows the performance of a model with no ability to predict fates of individual fish.

Figure 3.6-3 Receiver Operating Curve Showing True and False Positive Rates of Assigning Juvenile Chinook Salmon to Georgiana Slough

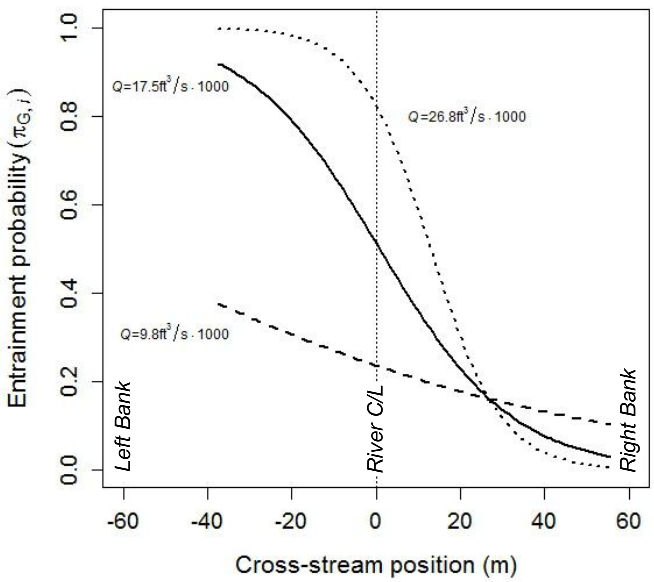
EFFECTS OF COVARIATES ON ENTRAINMENT PROBABILITY FOR CHINOOK SALMON

The best-fit model for Chinook salmon included interaction terms. Because of the interaction between *Q* and *X*, the effect of cross-stream position on $\pi_{G,i}$ depended on the amount of river discharge. The slope for cross-stream position was negative at all values of discharge (**Figure 3.6-4A**), indicating that $\pi_{G,i}$ decreased moving from the Georgiana Slough side of the river channel to the Sacramento River side of the channel (**Figure 3.6-5**). However, the magnitude of the slope for *X* increased (i.e., became more negative) with flow, indicating that higher flows increase the gradient of $\pi_{G,i}$ across the river channel. For example, at high flows, $\pi_{G,i}$ transitions sharply from near 0 at *X* = 30 m to near 1 at *X* = -20 m, whereas this transition is more gradual at lower flows (**Figure 3.6-5**). Likewise, the slope for *Q* decreases as *X* increases, but the slope switches from positive to negative at about *X* = 25 m (**Figure 3.6-4B**). Therefore, $\pi_{G,i}$ increases with flow for fish located on the Georgiana Slough side of the channel but decreases with flow for fish located toward the Sacramento River side of the channel (**Figure 3.6-6**).



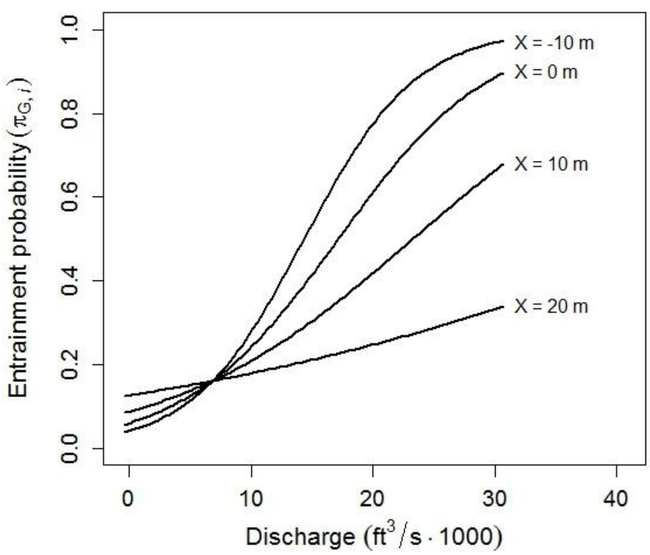
Notes:
Each panel shows the slope coefficient of one variable at fixed values of the other variable. Curves are plotted over the range of observed discharge and cross-stream positions.

Figure 3.6-4 Effect of the Interaction between Discharge Entering the River Junction (Q) and Cross-Stream Position of Tagged Chinook Salmon (X)



Notes:
Effect of cross-stream position (X) of acoustically tagged juvenile salmon on probability of entrainment into Georgiana Slough (Left side of center line) at the 5th (dashed line), 50th (solid line), and 95th (dotted line) percentiles of discharge. Curves are plotted over the observed range of cross-stream positions with BAFF Off at the mean streakline of -8.35 m.

Figure 3.6-5 Effect of Cross-Stream Position of Juvenile Chinook Salmon on Probability of Entrainment into Georgiana Slough under Different Discharges



Note:
Curves are plotted over the range of observed discharge with the BAFF Off at the mean streakline of -8.35 m.

Figure 3.6-6 Effect of Discharge on Probability of Entrainment into Georgiana Slough for Juvenile Chinook Salmon at Different Cross-Stream Locations

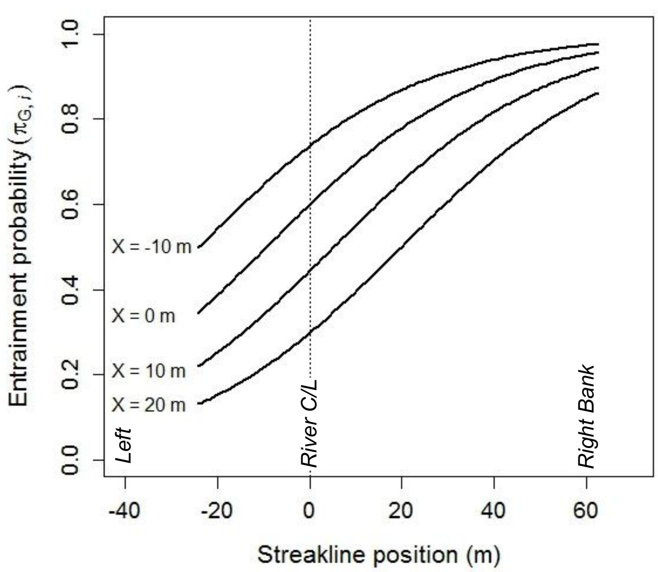
Parameter estimates indicate the effect of the other covariates on the probability of fish entering Georgiana Slough. The slope estimate for streakline (S) was positive, indicating that as the streakline moves in a positive direction (i.e., toward the Sacramento side of the river channel), the probability of fish entering Georgiana Slough increases (**Table 3.6-2**, **Figure 3.6-7**). For example, for fish located at X = -10 m, $\pi_{G,i}$ increases from about 0.5 to 1.0 at the mean observed discharge when the BAFF was off (**Figure 3.6-7**). The negative coefficient for B, where B = 1 representing times when the BAFF was on, indicated that operation of the BAFF reduced the probability of fish entering Georgiana Slough (**Table 3.6-2**). At the mean observed discharge, entrainment probability when the BAFF was on was up to 25 percentage points lower than when the BAFF was off, depending on the cross-stream position of fish (**Figure 3.6-8A** and **B**).

The findings indicate that the spatial zone of influence of the BAFF varied with the amount of discharge entering the river junction. Operation of the BAFF reduced the probability that fish would be entrained into Georgiana Slough by up to ~25 percentage points (**Figure 3.6-8B**). The greatest zone of BAFF influence occurred in a 20-meter section of the channel (from about *X* = -20 to about *X* = 0). The influence of the BAFF decreased to near 0 for fish located more toward the Sacramento side of the channel. Similarly, the influence of the BAFF decreased slightly as cross-stream location became more negative for mean conditions.

Table 3.6-2
Parameter Estimates for the Best-Fit Model for Juvenile Chinook Salmon

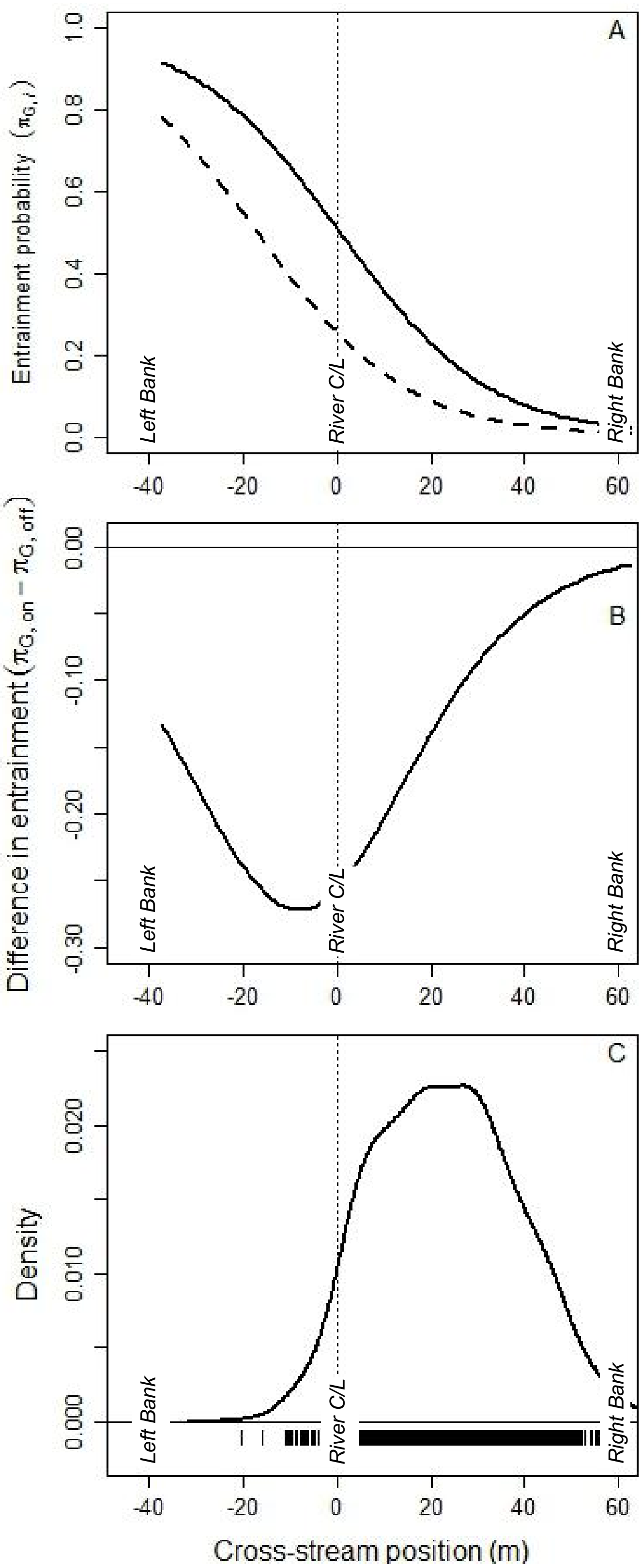
Variable	Parameter Estimate	Standard Error	95% Confidence Interval
Intercept (Off)	-2.914	0.506	-3.922, -1.936
B	-0.981	0.181	-1.341, -0.631
S	0.077	0.011	0.055, 0.1
Q	0.191	0.028	0.138, 0.248
X	0.053	0.021	0.012, 0.093
*Q*X*	-0.006	0.001	-0.009, -0.004

Notes: Variables defined as follows: *B* = BAFF operation (On = 1, Off = 1), *Q* = discharge, *S* = critical streakline, and *X* = cross-stream position of fish. The reference group for the intercept is *B* = off.



Notes:
Curves are plotted over the range of observed streakline positions with the BAFF Off at the mean discharge of 17.52 cfs·1000.

Figure 3.6-7 Effect of Streakline Position on Probability of Entrainment of Chinook Salmon into Georgiana Slough for Fish at Different Cross-Stream Locations (X)



Notes:

(A) presents the probability of entrainment into Georgiana Slough with the BAFF off (solid line) and BAFF on (dashed line) at the mean discharge of 17.65 cfs·1000 and mean streakline of -8.48 m.

(B) the difference in estimated entrainment between BAFF On and BAFF Off, and (C) the cross-sectional distribution of fish.

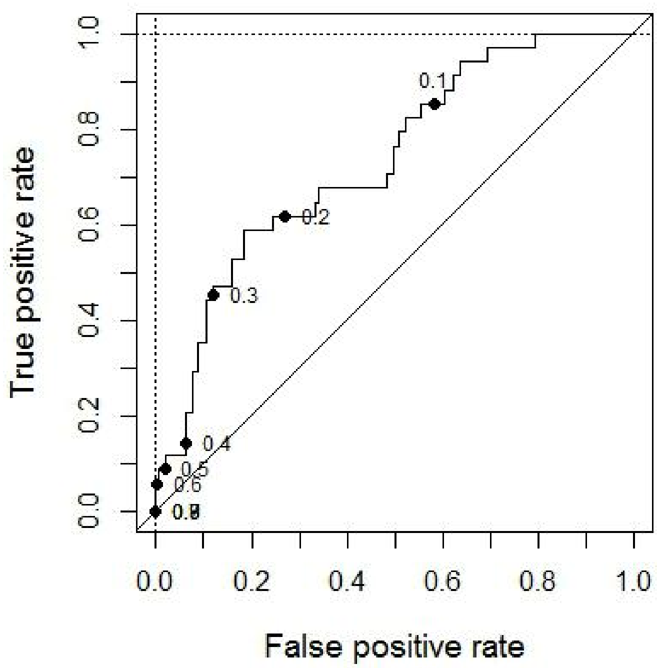
(C) the distribution was based on a kernel density estimator and the rug plot shows observed cross-stream positions of fish.

Figure 3.6-8 Probability of Entrainment of Juvenile Chinook Salmon into Georgiana Slough as a Function of Cross-Stream Position for BAFF Off and BAFF On

MODEL SELECTION RESULTS FOR STEELHEAD

Model selection results for steelhead suggested that discharge (*Q*) and cross-stream position (*X*) had the largest influence on entrainment. These covariates were followed by BAFF operation (*B*), streakline (S), along-stream location (*A*), and time of day (*D*). Among the two-parameter models, the model including discharge and cross-stream location had the lowest BIC value of all the models fit to the data. The model including BAFF operation (*B*) and discharge (*Q*) was ranked second. The three-parameter model including discharge (*Q*), cross-stream location (*S*), and BAFF operation (*B*) provided the best fit of group 5, but it was ranked below the best-fitting two-parameter model. Although BAFF operation was not included in the best-fit model, given the purpose of the study, BAFF operation was included in the final model to examine its role in entrainment into Georgiana Slough. Models that included interactions did not improve model fit and were ranked similarly to the intercept-only model; thus, the final selected model did not include any interactions. The final model consisted of the following main effects: discharge, cross-stream position, and BAFF operation.

Goodness-of-fit diagnostics showed acceptable fit. The Hosmer-Lemeshow goodness-of-fit test was not significant ($\hat{C} = 19.19$, df = 17, P = 0.318), and the AUC was 0.748, indicating that the model had an average ability to predict the fates of individual fish. A cutoff of >0.2 accurately predicted 59 percent of the fish that entered Georgiana Slough and incorrectly assigned 41 percent of the fish with a Sacramento River fate to Georgiana Slough (**Figure 3.6-9**).



Notes:

Results are based on cutoff values of πG ranging from zero to one (shown as labeled data points). The 45° reference line shows the performance of a model with no ability to predict fates of individual fish.

Figure 3.6-9 Receiver Operating Curve Showing True and False Positive Rates of Classifying Juvenile Steelhead to Georgiana Slough

EFFECTS OF COVARIATES ON ENTRAINMENT PROBABILITY FOR STEELHEAD

As described for Chinook salmon, the probability that steelhead would be entrained into Georgiana Slough increased for all cross-stream positions as discharge increased (**Figures 3.6-10** and **3.6-11**). Although entrainment increased across all cross-stream positions, the rate of change of entrainment was greater for higher flows as cross-stream positions became more negative.

Model selection results for logistic regression expressing the probability of juvenile steelhead entering Georgiana Slough as a function of covariates were similar to those for Chinook salmon and are presented in **Table 3.6-3**. Parameter estimates for steelhead were also similar to those for Chinook salmon (**Table 3.6-4**). Cross-stream position (*X*) had a negative slope, illustrating that as cross-stream position became more positive (i.e., closer to the Sacramento side of the river), entrainment probability decreased. Discharge had a positive slope, suggesting that as discharge increased, entrainment probability increased. Although BAFF operation did not appear in the lowest-BIC model, the coefficient for BAFF operations had a negative sign, providing evidence that operation of the BAFF reduced entrainment into Georgiana Slough (**Table 3.6-4**).

Table 3.6-3
Model Selection Results for Logistic Regression Expressing the Probability of Juvenile Steelhead Entering Georgiana Slough as a Function of Covariates

Model	Group	Number of Variables	NLL	BIC	Group ΔBIC	Overall ΔBIC
*B + X + Q + X * B*	1	4	77.76	181.83	0	8.45
*B + X + Q + X * Q*	1	4	77.79	181.9	0.07	8.52
*B + X + Q + Q * B*	1	4	77.81	181.94	0.11	8.56
*B + X + Q + A + A * B*	1	5	77.04	185.65	3.82	12.27
*B + X + Q + D + D * B*	1	5	77.33	186.23	4.4	12.85
*B + X + Q + D + X * D*	1	5	77.66	186.91	5.07	13.53
B + S + Q + X + D + A	2	6	77.81	192.46	0	19.08
B + S + Q + X + A	3	5	77.84	187.25	0	13.87
B + Q + X + D + A	3	5	77.93	187.43	0.18	14.05
B + S + Q + X + D	3	5	77.94	187.46	0.21	14.08
S + Q + X + D + A	3	5	78.54	188.66	1.41	15.28
B + S + Q + D + A	3	5	81.84	195.27	8.02	21.89
B + S + X + D + A	3	5	83.39	198.35	11.1	24.97
B + Q + X + A	4	4	77.93	182.17	0	8.79
B + S + Q + X	4	4	77.95	182.21	0.04	8.83
B + Q + X + D	4	4	78.03	182.38	0.2	9
S + Q + X + A	4	4	78.58	183.47	1.3	10.09
S + Q + X + D	4	4	78.65	183.6	1.43	10.22
Q + X + D + A	4	4	78.72	183.75	1.57	10.37
B + S + Q + A	4	4	81.89	190.1	7.92	16.72

Table 3.6-3
Model Selection Results for Logistic Regression Expressing the Probability of Juvenile Steelhead Entering Georgiana Slough as a Function of Covariates

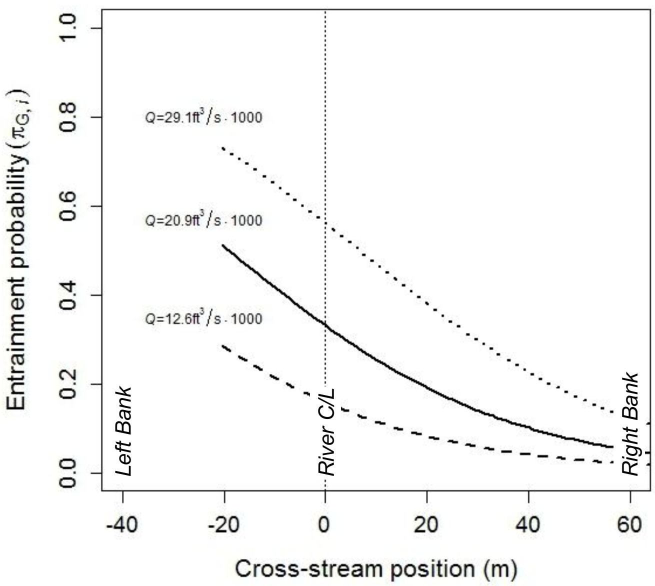
Model	Group	Number of Variables	NLL	BIC	Group ΔBIC	Overall ΔBIC
$B + Q + D + A$	4	4	81.91	190.13	7.95	16.75
$B + S + Q + D$	4	4	82.08	190.47	8.29	17.09
$S + Q + D + A$	4	4	83.06	192.43	10.26	19.05
$B + X + D + A$	4	4	83.39	193.1	10.92	19.72
$B + S + X + A$	4	4	83.4	193.12	10.95	19.74
$B + S + X + D$	4	4	83.47	193.25	11.08	19.87
$S + X + D + A$	4	4	86.16	198.62	16.45	25.24
$B + S + D + A$	4	4	86.31	198.94	16.77	25.56
$B + Q + X$	5	3	78.03	177.11	0	3.73
$S + Q + X$	5	3	78.67	178.38	1.27	5
$Q + X + A$	5	3	78.72	178.5	1.39	5.12
$Q + X + D$	5	3	78.79	178.64	1.53	5.26
$B + Q + A$	5	3	81.93	184.91	7.8	11.53
$B + S + Q$	5	3	82.1	185.25	8.13	11.87
$B + Q + D$	5	3	82.12	185.28	8.17	11.9
$S + Q + A$	5	3	83.13	187.3	10.19	13.92
$Q + D + A$	5	3	83.2	187.45	10.34	14.07
$S + Q + D$	5	3	83.25	187.55	10.43	14.17
$B + X + A$	5	3	83.41	187.86	10.75	14.48
$B + X + D$	5	3	83.48	188.01	10.89	14.63
$B + S + X$	5	3	83.5	188.05	10.94	14.67
$X + D + A$	5	3	86.16	193.37	16.25	19.99
$S + X + A$	5	3	86.19	193.43	16.32	20.05
$S + X + D$	5	3	86.25	193.54	16.43	20.16
$B + S + A$	5	3	86.32	193.69	16.57	20.31
$B + D + A$	5	3	86.32	193.69	16.57	20.31
$B + S + D$	5	3	86.5	194.05	16.94	20.67
$S + D + A$	5	3	89.65	200.34	23.23	26.96
$Q + X$	6	2	78.8	173.38	0	0
$B + Q$	6	2	82.13	180.04	6.66	6.66
$Q + A$	6	2	83.23	182.25	8.86	8.87
$S + Q$	6	2	83.29	182.36	8.98	8.98
$Q + D$	6	2	83.36	182.51	9.12	9.13
$B + X$	6	2	83.5	182.8	9.41	9.42

Table 3.6-3 Model Selection Results for Logistic Regression Expressing the Probability of Juvenile Steelhead Entering Georgiana Slough as a Function of Covariates						
Model	**Group**	**Number of Variables**	**NLL**	**BIC**	**Group ∆BIC**	**Overall ∆BIC**
$X + A$	6	2	86.19	188.17	14.79	14.79
$X + D$	6	2	86.25	188.29	14.9	14.91
$S + X$	6	2	86.3	188.39	15	15.01
$B + A$	6	2	86.32	188.44	15.05	15.06
$B + S$	6	2	86.5	188.79	15.41	15.41
$B + D$	6	2	86.51	188.81	15.42	15.43
$D + A$	6	2	89.65	195.08	21.7	21.7
$S + A$	6	2	89.65	195.08	21.7	21.7
$S + D$	6	2	89.85	195.48	22.1	22.1
Q	7	1	83.37	177.27	0	3.89
X	7	1	86.3	183.13	5.85	9.75
B	7	1	86.51	183.55	6.27	10.17
A	7	1	89.65	189.82	12.55	16.44
D	7	1	89.85	190.22	12.94	16.84
S	7	1	89.85	190.22	12.95	16.84
Intercept only	7	0	89.85	184.96	0	11.58

Notes: NLL = negative log-likelihood, BIC = Bayesian Information Criterion, and ∆BIC is the difference in BIC of each model relative to the lowest BIC model (either within groups of models or over all models).

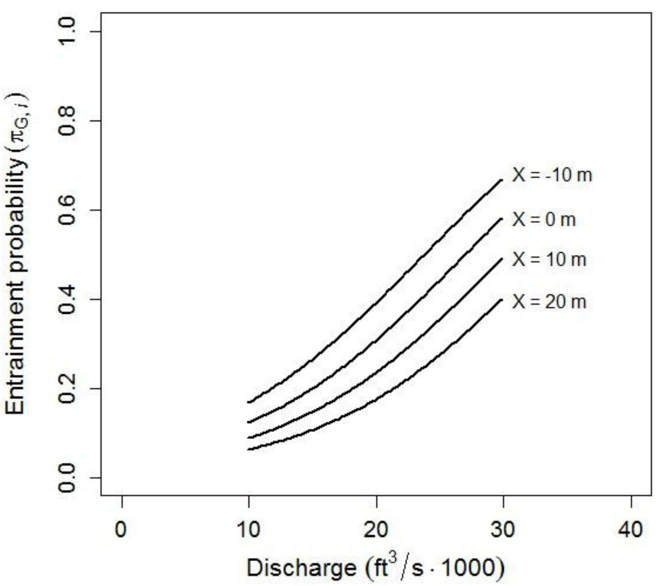
Table 3.6-4 Parameter Estimates for the Best-Fit Model for Juvenile Steelhead			
Variable	**Parameter Estimate**	**Standard Error**	**95% Confidence Interval**
Intercept (Off)	-3.879	1.162	-6.336, -1.756
X	-0.034	0.012	-0.059, -0.011
Q	0.137	0.045	0.053, 0.232
B	-0.554	0.454	-1.48, 0.318

Notes: Variables defined as follows: *B* = BAFF operation (On = 1, Off = 1), *Q* = discharge, and *X* = cross-stream position of fish. The reference group for the intercept is *B* = off.



Note:
Effect of cross-stream position (*X*) of acoustically tagged juvenile steelhead on probability of entrainment into Georgiana Slough (left side of center line) at the 5th (dashed line), 50th (solid line), and 95th (dotted line) percentiles of discharge. Curves are plotted over the observed range of cross-stream positions with BAFF Off.

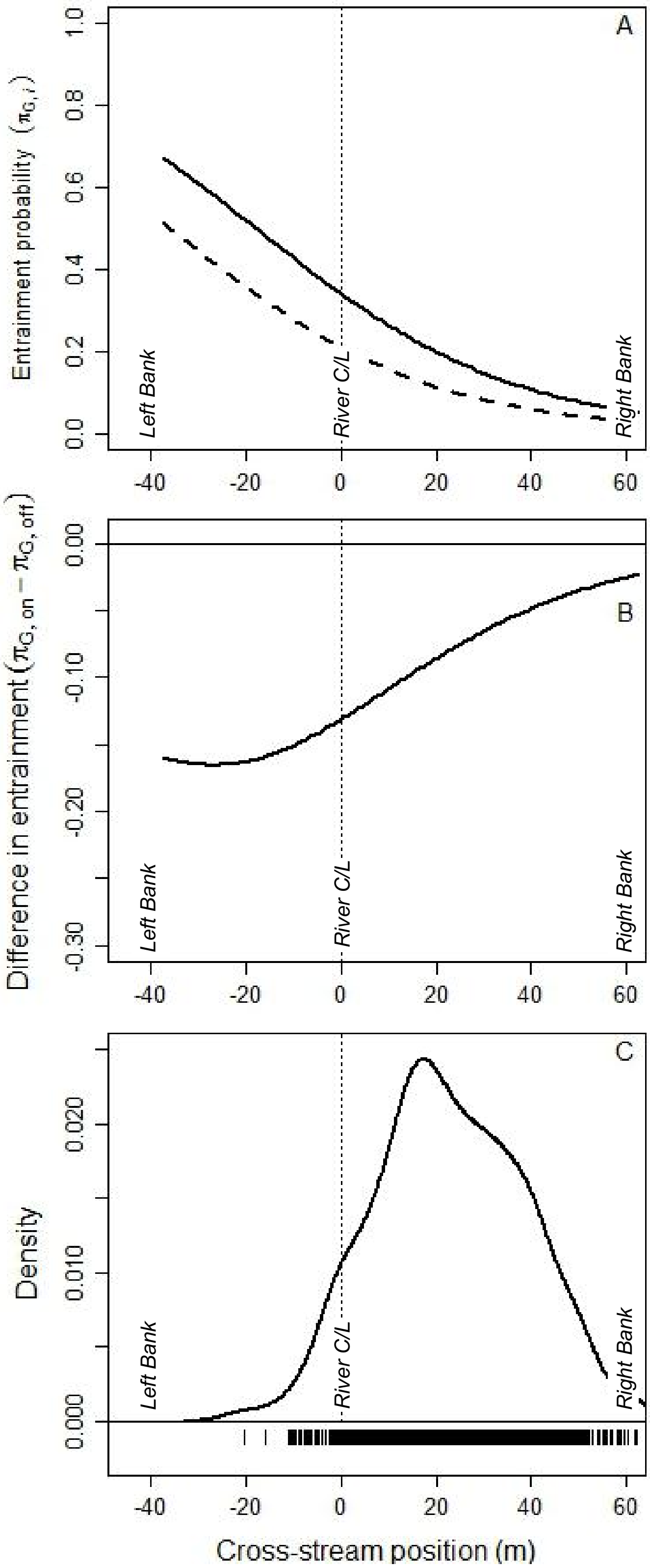
Figure 3.6-10 Effect of Cross-Stream Position of Juvenile Steelhead on Probability of Entrainment into Georgiana Slough under Different Discharges



Note:
Curves are plotted over the range of observed discharge with the BAFF Off.

Figure 3.6-11 Effect of Discharge on Probability of Entrainment into Georgiana Slough for Juvenile Steelhead at Different Cross-Stream Locations

For steelhead, the zone of BAFF influence increased as cross-stream position became more negative (i.e., moved toward the Georgiana Slough side [left bank] of the channel). The greatest zone of influence occurred in the region between X = -40 and X = -20, where entrainment was reduced by about 17 percentage points at mean observed discharge (**Figure 3.6-12**). Steelhead were primarily distributed at about X = 20. In this region, the BAFF reduced entrainment by about 10 percentage points at mean observed discharge.



Notes:

(A) presents the probability of entrainment into Georgiana Slough with the BAFF off (solid line) and BAFF on (dashed line) at the mean discharge of 22.26 cfs·1000.

(B) the difference in estimated entrainment between BAFF On and BAFF Off.

(C) the cross-sectional distribution of fish. The distribution was based on a kernel density estimator and the rug plot shows observed cross-stream positions of fish.

Figure 3.6-12 Probability of Entrainment of Juvenile Steelhead into Georgiana Slough as a Function of Cross-Stream Position for BAFF Off and BAFF On

Simulating BAFF Effects

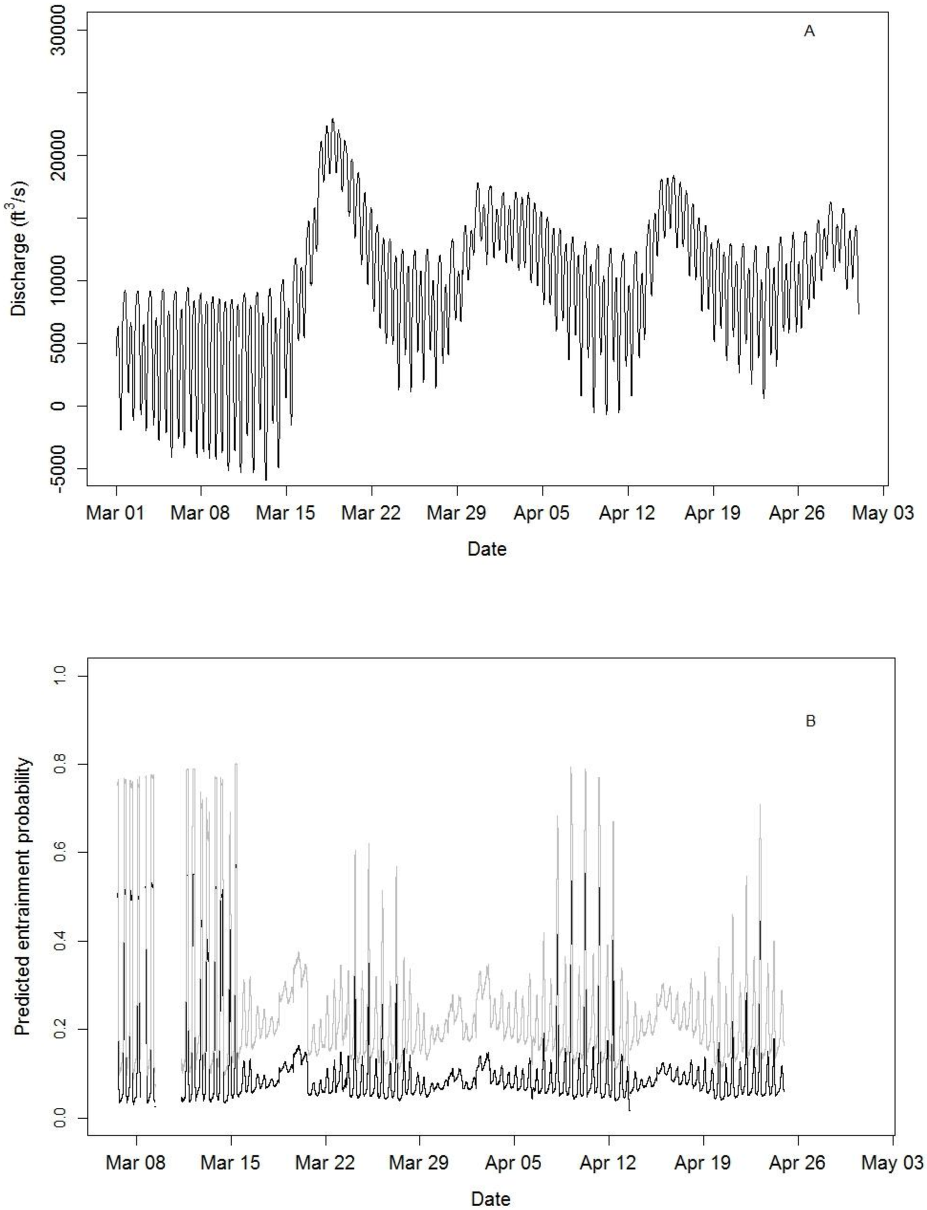
Simulation results illustrate the effectiveness of the BAFF under different hydrodynamic conditions experienced during the study period (**Figure 3.6-13**). In the beginning of the study during the lowest flows, entrainment probabilities into Georgiana Slough increased considerably regardless of BAFF operation because of flow reversals that forced the streakline to the right bank of the Sacramento River ($S = 60$). Hydrodynamics at the Georgiana Slough junction are complex, but typically when flows reverse because of tidal forcing, flow moves upstream from below the junction and into Georgiana Slough (see Section 3.4 and **Appendix F**). Although entrainment probabilities increase substantially under these conditions, operation of the BAFF was predicted to reduce entrainment. The simulations predicted that the BAFF would have the greatest influence in this situation, as is seen on **Figure 3.6-14**. Differences in predicted entrainment were greatest in this flow reversal scenario. In general, the simulations illustrate that the BAFF is more effective at reducing entrainment during lower flows and less effective during higher flows.

Estimating Entrainment into Georgiana Slough

Not surprisingly, fish location in the cross-section was the most important driver of an individual's probability of entrainment into Georgiana Slough. Common sense dictates that fish along the Sacramento River shoreline will remain in the Sacramento River when flows are positive or in the downstream direction and that fish along the shoreline entering Georgiana Slough will enter that channel. However, including cross-stream position in the analysis revealed where in the cross-section fish became vulnerable to entrainment into Georgiana Slough and where the BAFF reduced, or failed to reduce, an individual's probability of entrainment.

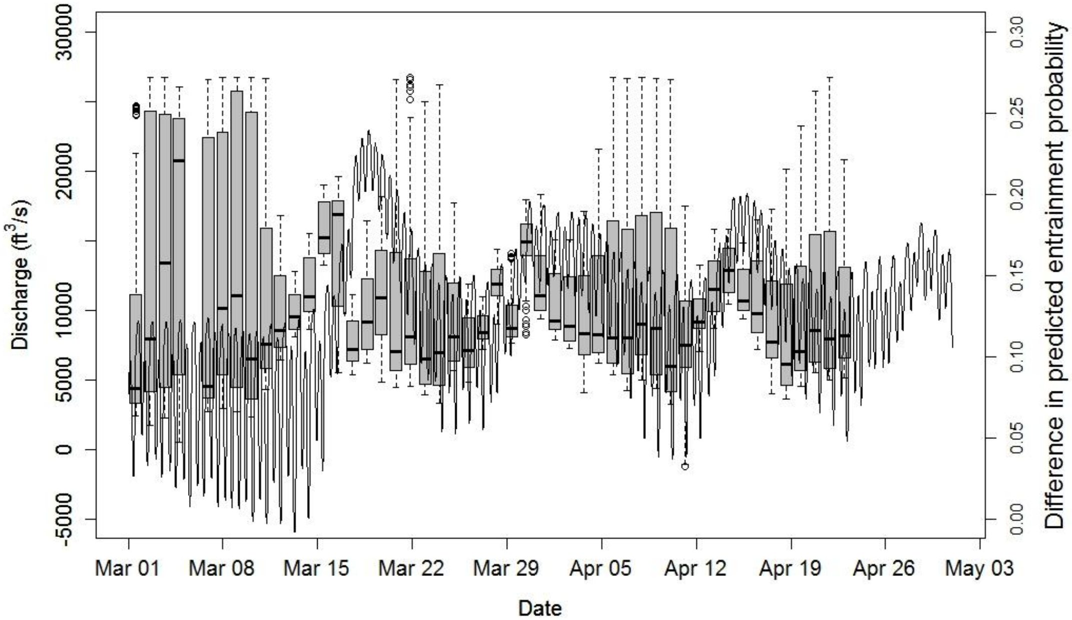
Under the flow regime experienced in 2012, the BAFF was effective at reducing entrainment probabilities for all cross-stream locations less than 60 m from the river centerline, or for most of the river channel. The influence of the BAFF was greatest in the region where fish would be close to the BAFF (**Figure 3.6-8B**). Cross-stream position was also critical for understanding how the cross-sectional distribution of fish drives overall entrainment by dictating the fraction of the population likely to come into contact with the BAFF or likely to enter Georgiana Slough. Such insights are critical for understanding how the BAFF affects individual entrainment probabilities and, subsequently, overall entrainment.

The findings show how an integrated, multisensory non-physical barrier was able to reduce, but not eliminate, entrainment into Georgiana Slough. Coutant (2001) makes a strong argument that behavioral guidance devices are likely to be most effective when different technologies are used in concert and tailored to a specific application. Along these lines, it was hypothesized that entrainment into Georgiana Slough could be reduced further by altering the cross-stream distribution of fish just upstream from the river junction. Relatively simple guidance structures, such as a shallow-draft floating boom, could be used to shift the cross-stream distribution toward the Sacramento River side of the channel. For example, a floating log boom at Lower Granite Dam on the Snake River was successful at guiding migrating juvenile salmon toward a surface passage structure (Plumb et al. 1999).



Note: Figure A presents discharge (the 15-minute time step), and Figure B presents the simulated entrainment probability of the BAFF On (black line) and BAFF Off (gray line) states at the mean daily cross-stream position.

Figure 3.6-13 Simulated Probability of Entrainment of Juvenile Chinook Salmon into Georgiana Slough for BAFF Off and BAFF On States



Note: This figure presents box plots of the daily differences in simulated entrainment probabilities for BAFF off and BAFF on (entrainment probability for BAFF off minus BAFF on, second y-axis). The boxes represent the median (solid line within box) and 25% and 75% quantiles, whereas the whiskers represent 5% and 95% quantiles. The solid line represents discharge (Q, first y-axis).

Figure 3.6-14 Differences in Simulated Entrainment Probabilities of Juvenile Chinook Salmon into Georgiana Slough for BAFF Off and BAFF On States

Given that entrainment probability dropped rapidly to 0 at $X > 10$ m (**Figure 3.6-8A**), the findings suggest that a small shift in the cross-stream distribution could have a large effect on the number of fish that enter Georgiana Slough. To gain insights about the potential effectiveness of using such guidance devices in tandem with the BAFF, the model could be used to simulate how altering the cross-stream distribution affects total entrainment, with and without operation of the BAFF (at least under the range of flows observed during the study). It should be noted that such a structure may also provide holding cover for predatory fishes and in turn increase juvenile salmon mortality in the area near the structure.

Although operating the BAFF succeeded in reducing entrainment into Georgiana Slough, success of the BAFF as a management tool needs to be considered in the context of improving survival of the population migrating through the Delta. The consequence of migrating through a given route must be measured to the point at which different routes ultimately converge (i.e., to Chipps Island [confluence of Sacramento and San Joaquin rivers]) (see Section 3.8).

The BAFF experiment was implemented under the hypothesis that reducing entrainment into the interior Delta would increase population-level survival by shifting fish from a low-survival migration route to a high-survival route. However, quantifying the magnitude of change in survival realized by operation of the BAFF was impossible because survival was measured over only a few kilometers downstream from the river junction. Furthermore, if operating the BAFF would substantially alter the abundance of juvenile salmon among migration routes, then predator distributions may also shift among routes in response to prey abundance. Future studies should quantify survival through the Delta during operation of the BAFF to better understand how within-route survival and overall survival change in response to altering the migration routes of juvenile Chinook salmon.

The GLM analysis has shown that the BAFF was effective at reducing entrainment into Georgiana Slough under most conditions found in the area. However, the BAFF was less effective at higher flows for fish located close to the Georgiana Slough side of the river channel. The mechanism behind this finding is likely the inability of a fish to alter its course away from the BAFF before being swept across the barrier and into Georgiana Slough. Given that juvenile fish have typical burst swimming speeds of approximately 1.5 m/s or 10 BL/s (Swanson et al. 2004), escape from entrainment may be physically unattainable at high flows. Fish may have tried to avoid the BAFF but were unable to do so and were entrained into Georgiana Slough.

3.7 ANALYSIS OF PREDATORS AND PREDATION

This section reports methods and results for four different analyses related to predators and predation. The different analyses included in this section are:

- Section 3.7.1, "Predator Detection," an analysis and evaluation procedure that could be used to estimate the probability of fish tracks being a predator and/or a salmonid based on movement diagnostics;
- Section 3.7.2, "Predator Movements,", an analysis of fine scale tracking movements to better understand patterns that are representative of predator species;
- Section 3.7.3, "Spatial Analysis of Tagged Predators and Predation Events," a spatial analysis of tagged predators and predations events with a focus on predator species occupancy times in different areas within the study array; and
- Section 3.7.4, Active Hydroacoustics," an analysis of split-beam sonar and DIDSON data to evaluate predator fish presence and densities in the array during different barrier operational conditions.

3.7.1 PREDATOR DETECTION

An issue inherent in tracking of tagged fish implanted with active telemetry tags is that the fish may be preyed on during the course of the studies (Kerstetter et al. 2004), potentially leading to incorrect conclusions about fish movement, behavior, and survival. This issue is especially problematic in the western rivers of the United States, where tagged juvenile salmonids may experience high mortality rates from predation during emigration (i.e., Fayram and Sibley 2000; Perry et al. 2010). More specific to this study, juvenile salmonids are often preyed on during their seaward migration through the Delta, which has been a major concern for telemetry-based survival studies (Mather 1998; Bowen et al. 2012; Vogel 2010). Survival studies assume that tag detections are from live juvenile salmonids, but tagged salmonids consumed by predatory fish (hereafter referred to as eaten salmonids) may be subsequently detected at downstream locations, leading to inflated survival estimates. Therefore, it is important to differentiate between detections of tagged salmonids that are alive and detections of eaten salmonids.

To date, few quantitative methods have been developed to distinguish between acoustic detections of live salmonids and acoustic detections of eaten salmonids in situations where recapture of the study fish is infeasible. Vogel (2011) proposed a three-step process that involves examining tag detections at three scales of resolution to determine the status of an acoustic tag (live salmonid or predator) based on expert opinion. The first and finest scale step consists of visual examination of the acoustic signal data as a tag moves past a receiver. The second step is to examine flow data at the time and location at which a tag is moving between receivers to determine whether the tag is moving against the flow, thereby providing evidence for predation. The final and coarsest scale step is to quantify the rate of tag movement through the array in comparison to the movement rate of the total tagged population. Movement rates falling in the tail of the distribution would be considered unlikely to have arisen from salmonid movements and subsequently would be classified as eaten salmonids. This three-step method has merit, but for large telemetry studies using thousands of tags, it is extremely laborious because it requires visual inspection of the entire detection history of each tag. Furthermore, because this method is based on expert opinion, it is subjective and could introduce bias or systematic variation among individuals examining the detection histories.

A detailed review of fish tracks may be useful in distinguishing between salmonids and predators and in potentially distinguishing between species of salmonids and predators. Under the assumption that emigrating salmonids and predators exhibit different movement behaviors, track characteristics such as sinuosity and tortuosity (i.e., a measure of a fish's lateral movement relative to forward movement) would likely differ between the two groups (Fayram and Sibley 2000; Melnychuk et al. 2010; Tabor et al. 2010). For example, to maximize the efficiency of migrating through the Delta, emigrating salmonids generally exhibit linear movement oriented with the direction of flow. Such movement would be characterized by shallow turning angles (Benhamou 2004; Svendsen et al. 2011). In contrast, the track of a foraging predator would likely exhibit steep turning angles and a nonlinear trajectory, consistent with hunting tactics. These assumed differences in movement behavior present an opportunity to use quantitative methods to classify tracks as those of a salmonid or those of a predator. Characteristics that would likely differ between salmonids and predators include turning angles and the length of the track between two successive locations (also referred to as step length) between consecutive 2D positions. More specifically, the turning angles in a track may be used to quantify the complexity or tortuosity of a track.

In addition, movement models have been developed to describe animal movement behavior. For example, correlated random walk models have been shown to describe the foraging behavior of some terrestrial predators (Austin et al. 2004). A characteristic of some correlated random walk models is Lévy walks (also known as Lévy flights) (Viswanathan et al. 2000; Bartumeus et al. 2005; Gurarie 2008). Lévy walks are characterized by clusters of short, seemingly random steps followed by less frequent and longer directed steps. In Lévy walks, the relationship between step lengths (l) and the frequency of occurrence of these step lengths follows a power function $f(l) = al^{-b}$ where a is an intercept parameter and b is the Lévy exponent.

In areas where prey are patchily distributed or in low abundance, predators often exhibit Lévy walk-type behavior. Compared with a simple correlated random walk search, this behavior has been shown to increase encounters with prey (Bartumeus et al. 2005; Sims et al. 2008). It follows that predators constrained by abiotic conditions, such as flow, may exhibit similar behavior, choosing to hold in optimal feeding lanes, moving small distances and making only periodic directed forays to other feeding areas (for example, in response to changing hydrodynamics caused by the tides). For predators exhibiting Lévy walk-type behavior, the Lévy exponent, b, typically ranges between 1 and 3. In contrast, the distribution of step lengths of a salmonid emigrating through a telemetry array is expected to be normally distributed (Melnychuk et al. 2010), which would yield a Lévy exponent near 0 (i.e., unrepresentative of a Lévy walk).

In this section, track statistics of known predators and fish tagged as salmonids but potentially eaten by predators are quantified. The first step was to estimate the Lévy exponent and tortuosity for each track. Following the assumption that the distribution of these track statistics differs between salmonids and predators, the study team then fit a bivariate normal mixture model to estimate the parameters of salmonid- and predator-specific distributions from the combined distribution of track statistics. Given these distributions, the team quantified the probability that any given track exhibited characteristics that were consistent with predator- or salmonid-like movement and used this information to classify the track as that of a salmonid or that of a predator.

METHODS

Fish tracks of juvenile Chinook salmon, juvenile steelhead, striped bass, smallmouth bass, and spotted bass were used in the analysis. They were truncated to detections occurring less than 159 m upstream and 333 m downstream of the uppermost point of the BAFF where the 2D array provided good coverage. Tracks with fewer than 60 2D positions were omitted from the analyses because the data were too sparse. Tags that had an average speed of less than 0.0009 m/s were also removed from the analyses because they were motionless tags that were likely defecated by predators. Ping rates of tags varied from two to four seconds. To normalize track data and avoid potential bias in track statistics that might arise from different variable ping rates between tags, tracks were rediscretized to a common time step. Tracks were rediscretized at a time step of 8 seconds using adehabitatLT package in R statistical software (R Development Core Team 2011). Discretizing involves using linear interpolation to estimate a tag's location based on the measured locations identified before and after the "missing" location. In addition, an 8-second time step was chosen to reduce "track wobble," which is an artifact of the acoustic positioning algorithm that could affect estimates of turning angle and the tortuosity estimate of the track. If time between detections was greater than 30 minutes, the track was split, and each track segment was analyzed separately. In other words, a tagged fish that moved through the array and then returned after 30 minutes or more was treated as two separate tracks. A track with a tortuosity value close to 1 was considered linear, whereas as the tortuosity value declines to 0, the track becomes more tortuous or complex.

Tortuosity (τ) was calculated as a function of the turning angle (θ):

$$\tau = \sqrt{\bar{x}^2 + \bar{y}^2}$$

where:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \cos(\theta_i)$$

and:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} \sin(\theta_i).$$

Lévy exponents were estimated as the slope of the linear regression between log-transformed step lengths and log-transformed step-length frequencies. The frequency was the number of occurrences of each step length in 0.1-m bins.

After track statistics were estimated for tagged salmonids and predators, finite mixture models were then fit to the distributions of track statistics using the mixtools package for R (Benaglia et al. 2009). Finite mixture models are a form of "model-based clustering" used to estimate parameters of mixed distributions for observations with unknown group membership. In this case, the bivariate distribution of track statistics (i.e., τ = tortuosity, b = Lévy exponent) was formed from a mixture of two underlying bivariate distributions: one for predators and one for salmonids. The goal was to use the finite mixture model to estimate the parameters of each bivariate distribution, which then allowed the study team to estimate the probability that each track segment came from a predator or salmonid.

The study team assumed that predators would exhibit greater turning angles, resulting in more tortuous tracks and Lévy parameters in the range of 1-3 (**Table 3.7-1**). In contrast, the team hypothesized that salmonids would exhibit a more directed path of movement, resulting in turning angles close to 0 and a tortuosity estimate close to 1, which is indicative of a linear path. Furthermore, a lower estimate of the Lévy parameter would be indicative of a salmonid swimming at a somewhat constant speed through the telemetry array.

Table 3.7-1
Assumptions for Mean Track Statistics of Salmonids and Predators

Track Statistic	Salmonid	Predator
Tortuosity (τ)	Higher	Lower
Lévy exponent (b)	Lower	Higher

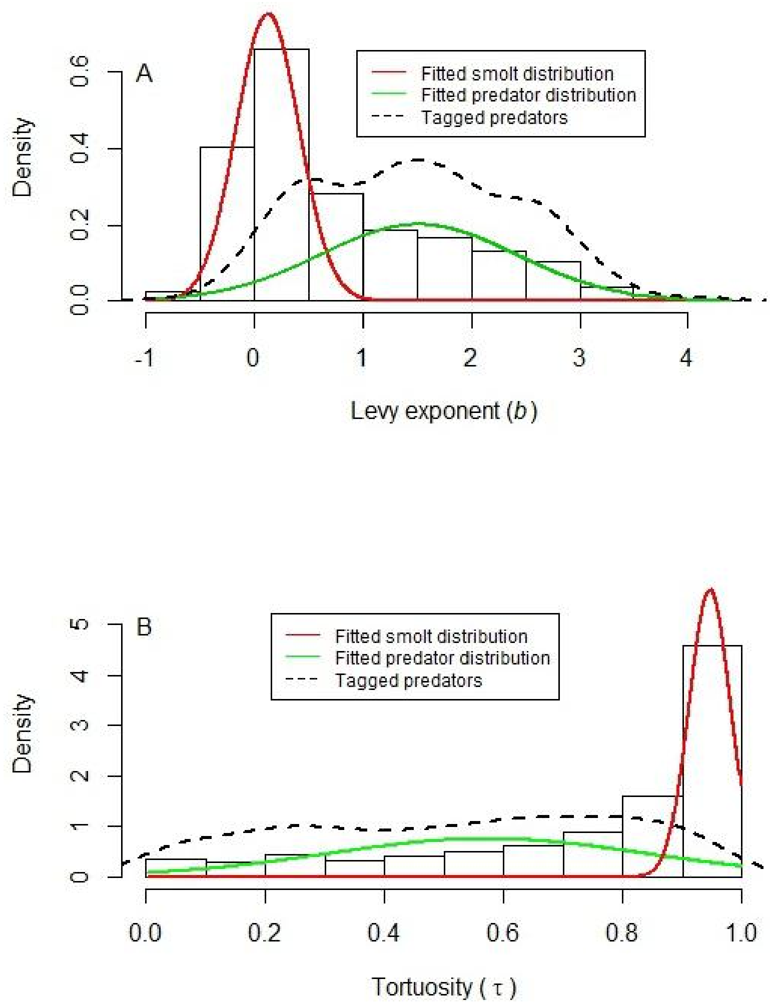
The study team used a mixture model that assumed that the distribution was a mixture of two bivariate normal distributions, each with an associated mean (μ) and standard deviation (σ). Thus, the mixture model estimated parameters of a normal distribution for salmonid- and predator-specific tortuosity and the Lévy exponents, resulting in eight parameters: $\mu_{S,b}$, $\sigma_{S,b}$, $\mu_{P,b}$, $\sigma_{P,b}$, $\mu_{S,\tau}$, $\sigma_{S,\tau}$, $\mu_{P,\tau}$, and $\sigma_{P,\tau}$. Here, μ_{jk} and σ_{jk} are the mean and standard deviation of a normal distribution for track statistic j (j = Lévy exponent (b) or tortuosity (τ)) and population k (k = predator (P) or salmonid (S)). In addition, the model also estimates λ_P, the proportion of track segments that are predators ($1-\lambda_P = \lambda_S$, the proportion of track segments that are salmonids). Last, to classify track segments as predator or salmonid, the team used the estimated parameters and the observed track statistics of each track segment to estimate p_{ik}, the probability that each track segment (i) could have been produced by a salmonid (k = S) or predator (k = P, see Equation 2 in Benaglia et al. 2009). Track segments were then classified as a predator if $p_{i,P} > p_{i,S}$ and a salmonid if $p_{i,P} \leq p_{i,S}$.

The study team evaluated classifications from the mixture model using two approaches. First, for tagged salmonids, classifications from the mixture model were compared to classifications made during the Fish Fates Conference. For this comparison, a tag from the conference was categorized as a predator if at any time during its movement history in the array it displayed characteristics of a predator. Likewise, for the mixture model, a tag was categorized as a predator if any individual track segment was classified as a predator. Second, for tagged predators, the team evaluated whether the mixture model correctly classified these tracks as predators. The team then constructed 2 x 2 cross-tabulation tables by species.

RESULTS

The hypotheses about the distributions of track statistics were supported by (1) the estimated distributions from the mixture model and (2) the observed distribution of track statistics from known predators (**Figure 3.7-1**). The fitted distributions for the Lévy parameter (b) were centered at 0.107 and 1.42 (**Table 3.7-2**), which are consistent with expectations of salmonid-like and predator-like behavior, respectively. The distribution of Lévy coefficients for known predators was similar to that estimated by the mixture model, lending further support to this approach.

Examples of tracks for assumed predators and salmonids show how the step-length distributions for predators typically followed a power function, characterized by a greater number of short steps than longer steps (**Figure 3.7-2**). In contrast, step lengths for salmonid-like tracks were approximately normally distributed with a slope close to 0 (**Figure 3.7-2**).

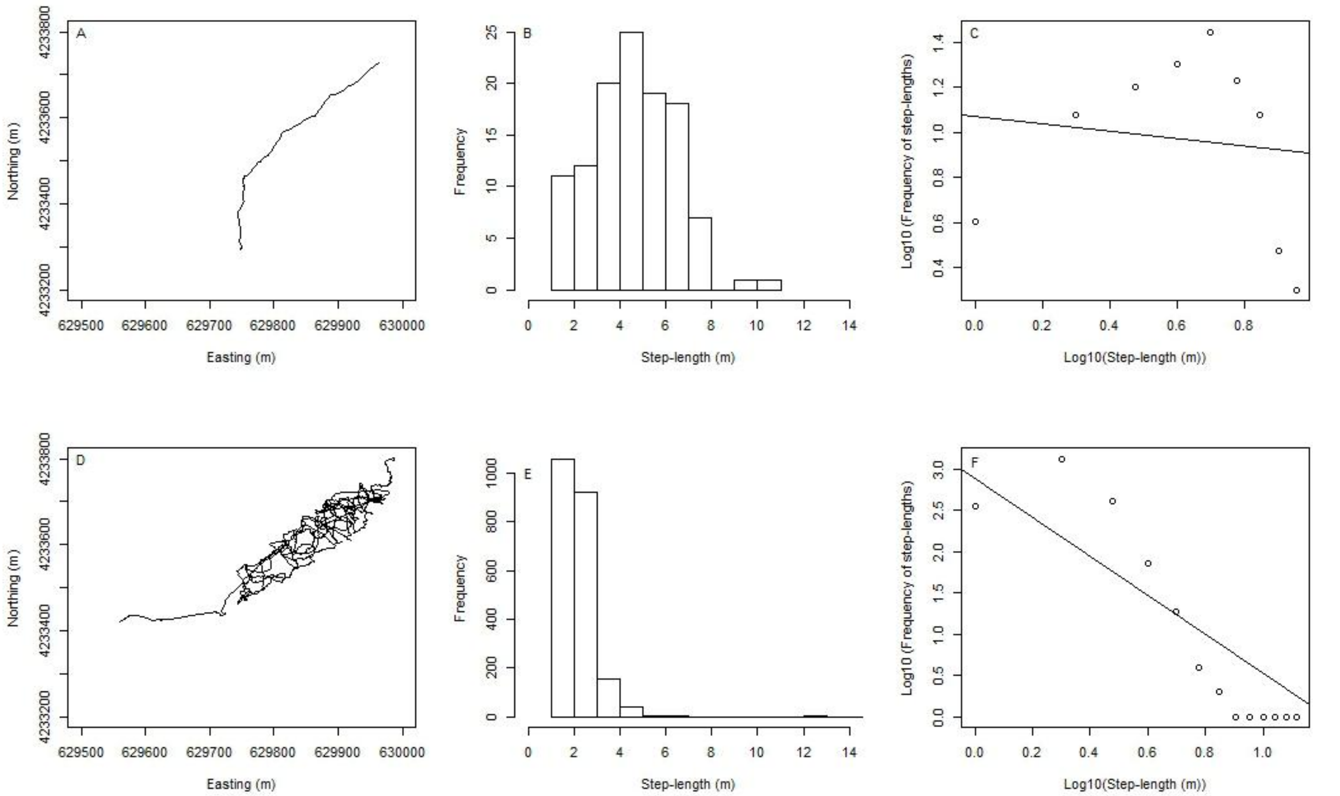


Note: The histogram shows the mixed empirical distribution of track statistics for which the true population assignment is unknown (i.e., predator or salmonid). The black dashed line shows the distribution of track statistics for known predators.

Figure 3.7.1 Distributions of the Lévy Exponent (A) and Tortuosity (B) for Salmonid (Red Line) and Predator (Green Line) Populations Estimated Using a Bivariate Mixture Model of Normal Distributions

Table 3.7-2
Parameter Estimates from Bivariate Mixture Model Showing the Estimated Mean and Standard Deviation of the Distributions of Track Statistics for Predator (P) and Salmonid (S)

Mean	Estimate	SD	Estimate
$\mu_{P,b}$	1.420	$\sigma_{P,b}$	0.841
$\mu_{S,b}$	0.107	$\sigma_{S,b}$	0.071
$\mu_{P,\tau}$	0.565	$\sigma_{P,\tau}$	0.092
$\mu_{S,\tau}$	0.945	$\sigma_{S,\tau}$	0.001



Note: Panels A and D show the 2D track, panels B and E show the distribution of step-length frequencies, and panels C and F show log_{10}-transformed step lengths versus log_{10}-transformed frequency of step lengths. Solid lines in panels C and F is the linear regression fit to the log-transformed data.

Figure 3.7-2 Comparison of Tracks for an Assumed Salmonid and Assumed Predator

The fitted distributions for tortuosity values were centered at 0.95 (sd = 0.035) and 0.55 (sd = 0.30), with an order of magnitude difference in the standard deviation of these distributions (**Table 3.7-2**). The distribution of tortuosity for known predators matched that estimated f or predators by the mixture model. These findings support the hypothesis that salmonids would have more linear, less tortuous tracks than predators.

In total, 1,420 Chinook salmon, 262 steelhead, 14 smallmouth bass, 6 spotted bass, and 29 striped bass tracks were analyzed. The approach using the mixture model accurately classified 86 percent of the striped bass, 100 percent of the smallmouth bass, and 100 percent of the spotted bass as predators (**Table 3.7-3**). Of the 1,420 Chinook salmon tracks analyzed, the approach classified 303 tracks as predators and 1,096 tracks as salmonids. The Fish Fates Conference classified a similar number of Chinook salmon tags as salmonids and predators, but the cross-tabulation revealed less agreement about which tags were classified as predators and which were classified as salmonids (**Table 3.7-3**). For example, 85 tags that were classified as Chinook salmon salmonids by the mixture model were classified as predators by the Fish Fates Conference, and 85 tags that were classified as predators by the mixture model were called Chinook salmon salmonids by the conference. Despite these discrepancies, there was good agreement between the mixture model and the Fish Fates Conference, with a common classification for 88 percent of Chinook salmon tags and 86 percent of Steelhead tags (**Table 3.7-3**). Last, the fates assigned during the Fish Fates Conference showed a slight tendency to classify more tracks as predators than the mixture model (**Table 3.7-3**). As opposed to known predator tags, reconciling classification differences between the mixture model and the fates assigned during the Fish Fates Conference is difficult because of the unknown true state of the tags (implanted in salmonids not eaten versus eaten).

Table 3.7-3
Cross-Tabulation Tables Showing Comparison between the Classification Using the Mixture Model Compared to the Fish Fates Conference and Known Predators

Chinook and Steelhead		Fish Fates Conference		
		Salmonid	Predator	Total
Mixture Model	Salmonid	1,159	109	1,268
	Predator	98	301	399
	Total	1,257	410	

Striped Bass		Known Predators	
		Salmonid	Predator
Mixture Model	Salmonid	NA	6
	Predator	NA	23
	Total	NA	29

Chinook		Fish Fates Conference		
		Salmonid	Predator	Total
Mixture Model	Salmonid	997	85	1,082
	Predator	85	241	326
	Total	1,082	326	

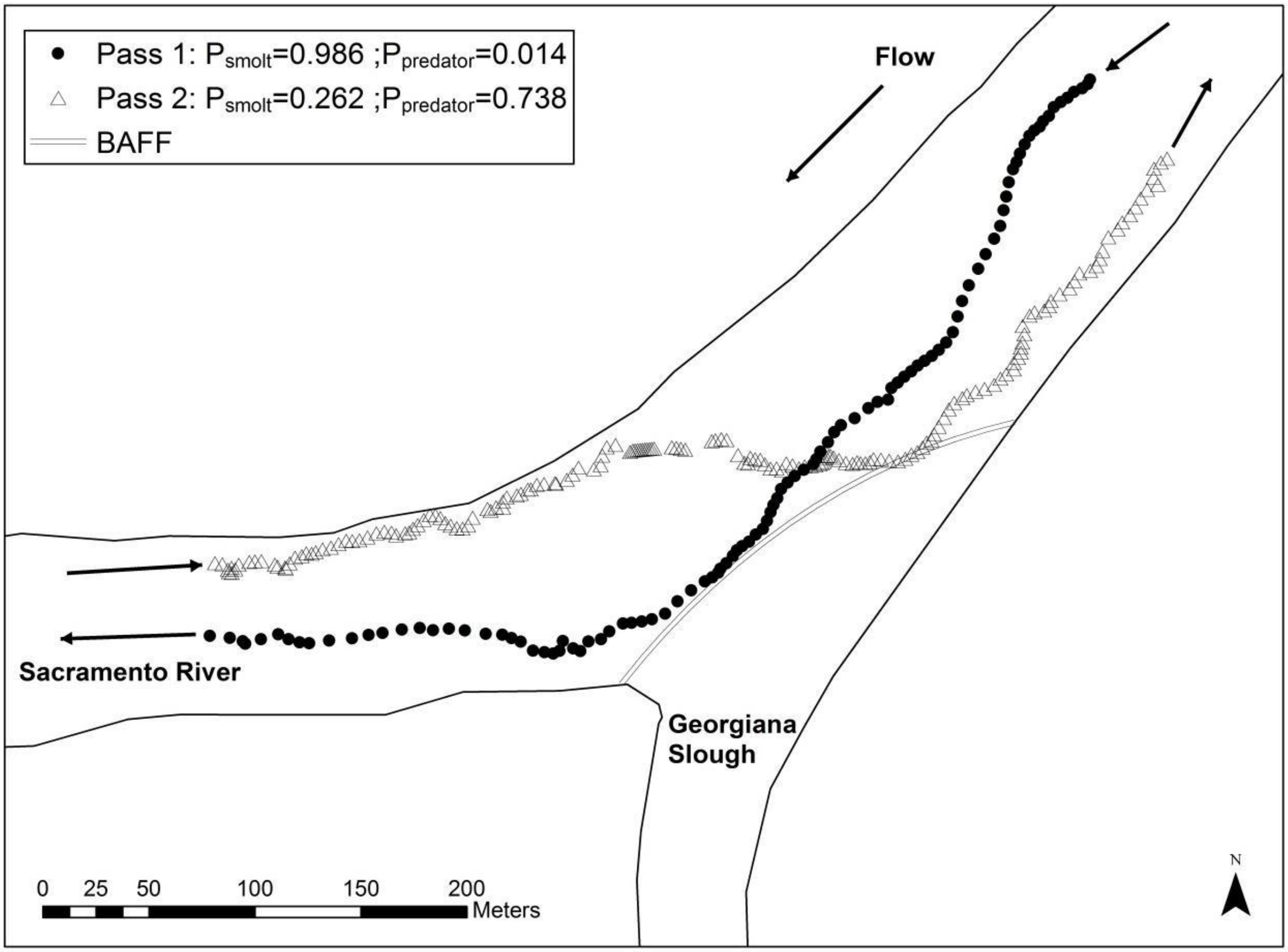
Smallmouth Bass		Known Predators	
		Salmonid	Predator
Mixture Model	Salmonid	NA	0
	Predator	NA	14
	Total	NA	14

Steelhead		Fish Fates Conference		
		Salmonid	Predator	Total
Mixture Model	Salmonid	162	24	186
	Predator	13	60	73
	Total	175	84	

Spotted Bass		Known Predators	
		Salmonid	Predator
Mixture Model	Salmonid	NA	0
	Predator	NA	6
	Total	NA	6

The total number of tracks includes multiple passes through the array by 237 tagged fish. A total of 156 Chinook salmon tracks consisted of multiple segments (see **Figure 3.7-3** for an example of a multiple-pass track). Of these 156 tracks, 113 were classified as predators by the Fish Fates Conference and the mixture model). Four were classified as salmonids by both the conference and the predator detector. Thirty-three were classified as predators by the conference but as salmonids by the predator detector. Forty-one steelhead had tracks with multiple segments. Of these, 25 were classified as predators.

The tagged predators yielded 784 track segments that were analyzed. Of these, 80 segments (10.2 percent) were classified as salmonids, and the remainder were classified as predators. Forty-two striped bass segments, six spotted bass segments, and 32 smallmouth bass segments were classified as salmonids.



Note: The first pass (solid circles) had a higher probability of being a salmonid ($P_{salmonid}$ = 0.986), and the second pass or upstream movement (triangles) had a greater probability of being a predator ($P_{predator}$ = 0.738).

Figure 3.7-3 Example of a Multiple-Pass Track (Acoustic Tag 2007.01) in the Study Area

Discussion

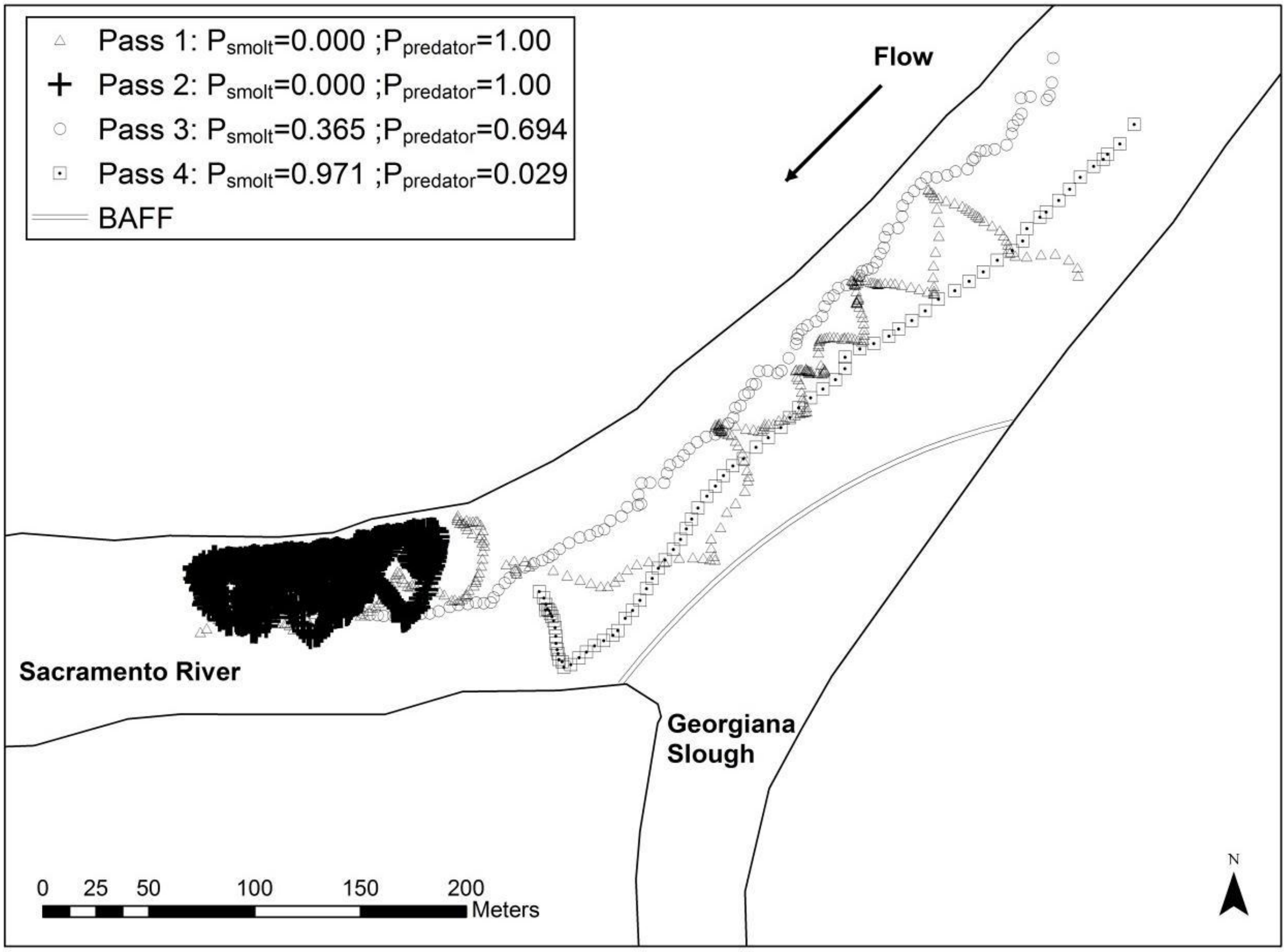
In any given telemetry study, researchers will seldom have information to verify whether detections from salmonid tags actually arise from movements of a predator that has eaten the salmonid. The mixture model approach used for this study explicitly accounts for the unknown state of tags (predator or salmonid) by using behavioral characteristics of movement paths to distinguish salmonid-like behavior from predator-like behavior. In general, the mixture model was able to clearly separate distributions of track statistics that were consistent with hypothesized salmonid and predator behavior. The mixture model also provided a probabilistic estimate of whether a given track segment arises from a predator or salmonid. Furthermore, although the “manual review” of tracks requires many person-weeks of labor and is subjective, the processing time for the mixture model is on the scale of hours.

The study team believes that using the mixture model approach provides a sound alternative to manual review of each track, but this approach does not entirely rule out classification schemes that include some level of manual review. Because the mixture model yields a probabilistic estimate of a track’s source population, there will be regions of high certainty that a track’s characteristics are consistent with a salmonid or predator, as well as regions of relative uncertainty where manual review may still provide a useful “second opinion” for a track’s classification. For example, one approach would be to divide the probability space into three equal-size regions (i.e., 0 to 0.33, 0.33 to 0.66, and 0.66 to 1). Tracks falling into the central region, where classification is less certain, could be reviewed manually, and auxiliary information (e.g., movement against the flow) could help inform the classification. Such an approach would provide a more systematic, quantitative method for classifying tracks while still retaining some level of manual review.

It is important to recognize that any classification method, be it statistical or manual, is unlikely to classify tracks with 100 percent accuracy because both predators and salmonids may exhibit multiple behavioral modes that lead to misclassification. That is, sometimes a predator may “look like” a salmonid, and sometimes a salmonid may “act like” a predator. This aspect of the fish behavior is captured in the mixing model as the region of overlap in the distributions of track statistics for predator and prey (**Table 3.7-3**). Specifically, the predator distribution overlaps the salmonid distribution, indicating that the predator tracks sometimes resemble the characteristics of a salmonid track. For example, one striped bass (acoustic tag 2238.15) had four distinct track segments, and each track segment had characteristics leading to classification as both salmonid and predator (**Figure 3.7-4**). The first two track segments were classified as a predator with near certainty, and the third was also classified as a predator but with higher uncertainty. In contrast, the final track was classified as a salmonid because the striped bass moved quickly through the array in a linear fashion.

Likewise, it is possible for salmonids to exhibit movement behavior that may be mistaken for that of a predator. Predator avoidance and holding during the daytime are two behavioral processes that could cause movement of salmonids to be classified as predators. Chapman et al. (2013) found significant differences in migration rates during the day and night for Chinook salmon salmonids in the Sacramento River. Chinook salmon migrated further during the night than during daytime hours, suggesting that some salmonids in the study may have exhibited holding behavior similar to predators during the day, when migration may have slowed (see also Section 3.5). Atlantic salmon have also been shown to have a preference for migrating during the nighttime hours rather than during the day (Ibbotson et al. 2006). Bradford and Higgins (2001) also reported lower activity levels for both juvenile Chinook and steelhead during the day. Notwithstanding multiple modes of behavior that would pose difficulty for any classification scheme, the mixture model approach provides a quantitative method for classifying behaviors that are most commonly associated with the movement of predators and salmonids.

Although the approach used for the current study provides a sound basis for estimating juvenile salmonid mortality from track examination, further research should be conducted in situ to verify this approach. The study team did not have a mechanism in place to verify the classification of eaten salmonids. Svedson et al. (2011) examined Atlantic salmon (*Salmo salar*) tracks as they passed a water diversion in Denmark. This study used a trap to verify that fish tracks used in behavioral analyses were tagged salmonids. Given the dynamics of the current study area, recapture of tagged fishes to verify the classifications would have been extremely difficult. However, 12 salmonid tags were observed that appeared to have been defecated in the array, suggesting that these fish had been eaten. These tags showed normal movement then ceased forward movement for the duration of the tag life. The algorithm classified these tags as predators—most on the first pass. These tags do provide support for the methods, but the team could not rule out other explanations. Other possible causes include tag shedding or mortality from other causes; however, tank studies suggest that tagging-related mortality and tag loss were not an issue (see **Appendix C**). Other approaches for verification of our methods might include the coupling of an intensive acoustic array and single hydrophones in adjacent areas. This would provide insights into the migratory behavior of the tagged fish that could be used to support or refute classifications created by the algorithm.



Note: Figure illustrates the different behaviors of a striped bass. Pass four had a higher probability of being a salmonid ($P_{salmonid}$ = 0.971) than a predator ($P_{predator}$ = 0.029), whereas all other passes had higher probabilities of being a predator ($P_{predator}$> $P_{salmonid}$).

Figure 3.7-4 Track of Acoustic Tag 2952.15, a Tagged Striped Bass in the Study Area

3.7.2 PREDATOR MOVEMENTS

METHODS

Tracks of four tagged predators were selected for movement analysis. The tracks were developed during the data collection period using the preliminary automated tracking process. The four predators represented three different species: two striped bass, one Sacramento pikeminnow, and one smallmouth bass. All the time spent by each predator in the Georgiana Slough study array between March 5, 2012, and April 30, 2012, was reflected in the tracks of these tagged predatory fish.

In addition, four tracks from tagged Chinook salmon salmonids were selected for comparison. The four salmonids selected were not assigned a fate of being eaten by a predator. Two of the selected salmonids entered Georgiana Slough, and two remained in the Sacramento River during their passage through the array.

Tracks were made up of individual position estimates at time intervals related to each tag period and secondary pulse interval. **Table 3.7-4** lists the acoustic tag transmission intervals for the overall period and secondary pulse of each selected tagged predator and salmonid. Each track was summarized into short line segments representing approximately 10-second intervals. Velocity vectors (speed and X-Y direction) were then calculated for each of these individual line segments for all track data for the selected tagged fish.

To investigate the effect of flow on predator movement, two hours (0600 to 0700 and 1400 to 1500) were selected from the same day of monitoring (March 26, 2012) when both predators and salmonids were present in the array but when the water velocity was different because of tidal conditions. Tracks of tagged fish present in the array during these two hours were also summarized into approximately 10-second intervals. The resulting line segments were then used to calculate mean speed over ground and sinuosity (total distance travelled divided by distance between start point and end point of the track) for each tagged fish in the array.

For those tagged fish that entered the array, became stationary, and remained so for the duration of the tag battery life (or the duration of the study), raw data files were examined to locate the time when tag motion ceased.

Table 3.7-4
Tag Periods and Secondary Pulse Intervals (Subcodes) for Selected Tagged Fish

Tagged Fish Species	Acoustic Tag Period		Subcode Interval	
	Milliseconds	Seconds	Subcode	Milliseconds
Sacramento pikeminnow	2,070	2.070	15	456
Smallmouth bass	2,028	2.028	15	456
Striped bass	2,154	2.154	15	456
Striped bass	2,910	2.910	15	456
Chinook salmon	3,939	3.939	19	548
Chinook salmon	2,742	2.742	12	423
Chinook salmon	2,532	2.532	25	647
Chinook salmon	2,175	2.715	28	710

RESULTS

Figure 3.7-5 shows the complete tracks of four tagged predators in the study array. Although the smallmouth bass (green tracks) and Sacramento pikeminnow (magenta tracks) tended to remain near the shore and only occasionally crossed the main channels, the striped bass (blue and yellow tracks) tended to remain in the main channels for a greater portion of the time relative to other predator species.

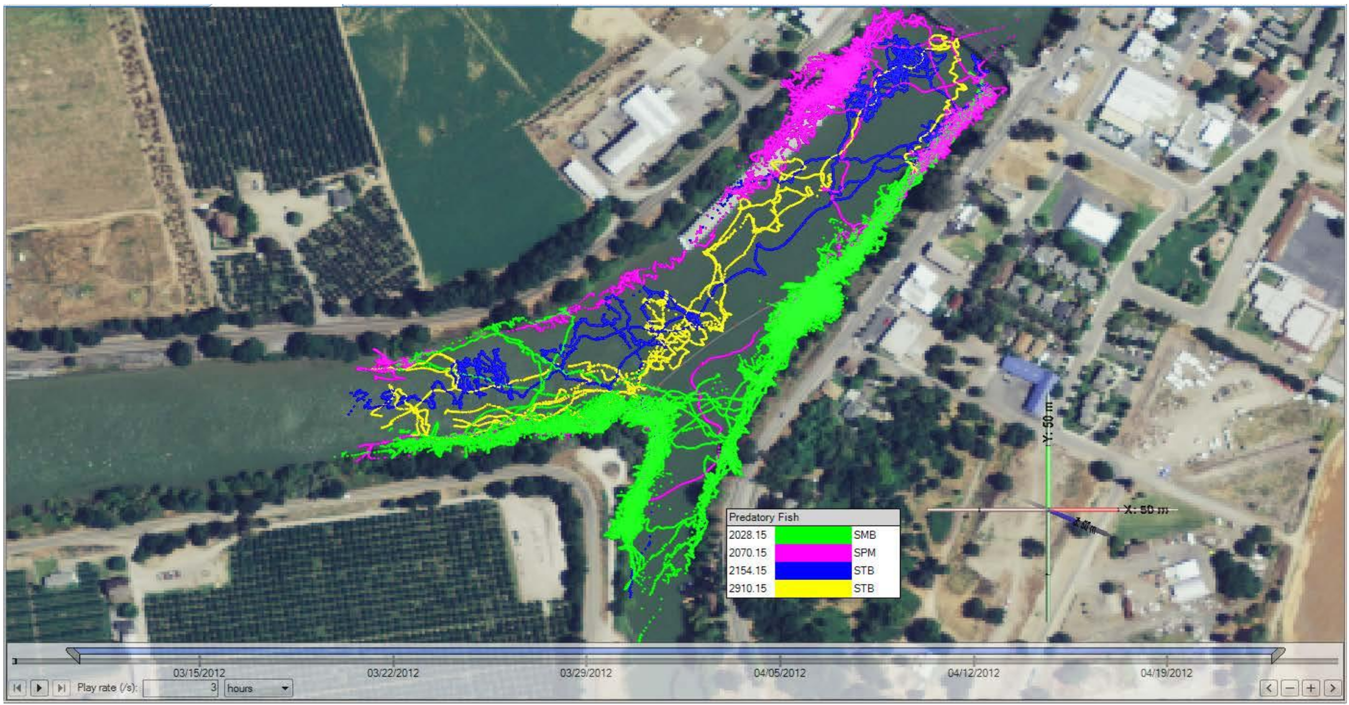


Figure 3.7-5 **Tracks of Four Tagged Predatory Fish, Georgiana Slough, Spring 2012**

Radar plots developed from the direction of travel for each approximately 10-second line segment of each predator track indicate that although the overall motions of the smallmouth bass and Sacramento pikeminnow were related to shore-oriented behavior, the overall motions of the striped bass covered a wider range of directions (**Figure 3.7-6**). Frequency histograms of speed over ground (calculated from the approximately 10-second line segments) for the four predators are shown on **Figure 3.7-7**.

Figures 3.7-8 and **3.7-9** show the same analyses and plots for four tagged Chinook salmon salmonids. In contrast to the radar plots developed for the predators, those developed for the selected tagged salmonids (**Figure 3.7-9**) indicate a narrow range of directions of overall motion. Frequency histograms of speed over ground for the Chinook salmon salmonids (**Figure 3.7-10**) show generally greater speeds of travel when compared to the predators.

Movements of tagged predators and tagged salmonids are affected by the water velocity at the time and the location of the fish. **Figure 3.7-11** shows the overall water velocity of the Sacramento River for the two hours selected for comparison of predator tracks and salmonid tracks during high-velocity (>2 ft/s; 1400-1500) and low-velocity (just over 0.25 ft/s; 0600-0700) conditions (**Figure 3.7-12**).

Migratory behavior would generally be indicated by downstream movement, few turns, and little upstream travel. This behavior would result in low values for sinuosity and higher values for speed over ground. **Figures 3.7-13** and **3.7-14** plot sinuosity against mean speed over ground for all fish in the study array during low-water-velocity conditions (**Figure 3.7-13**) and high-water-velocity conditions (**Figure 3.7-14**). Tags indicated as “predation salmonids” were tagged Chinook salmon classified as having been eaten by an untagged predator.

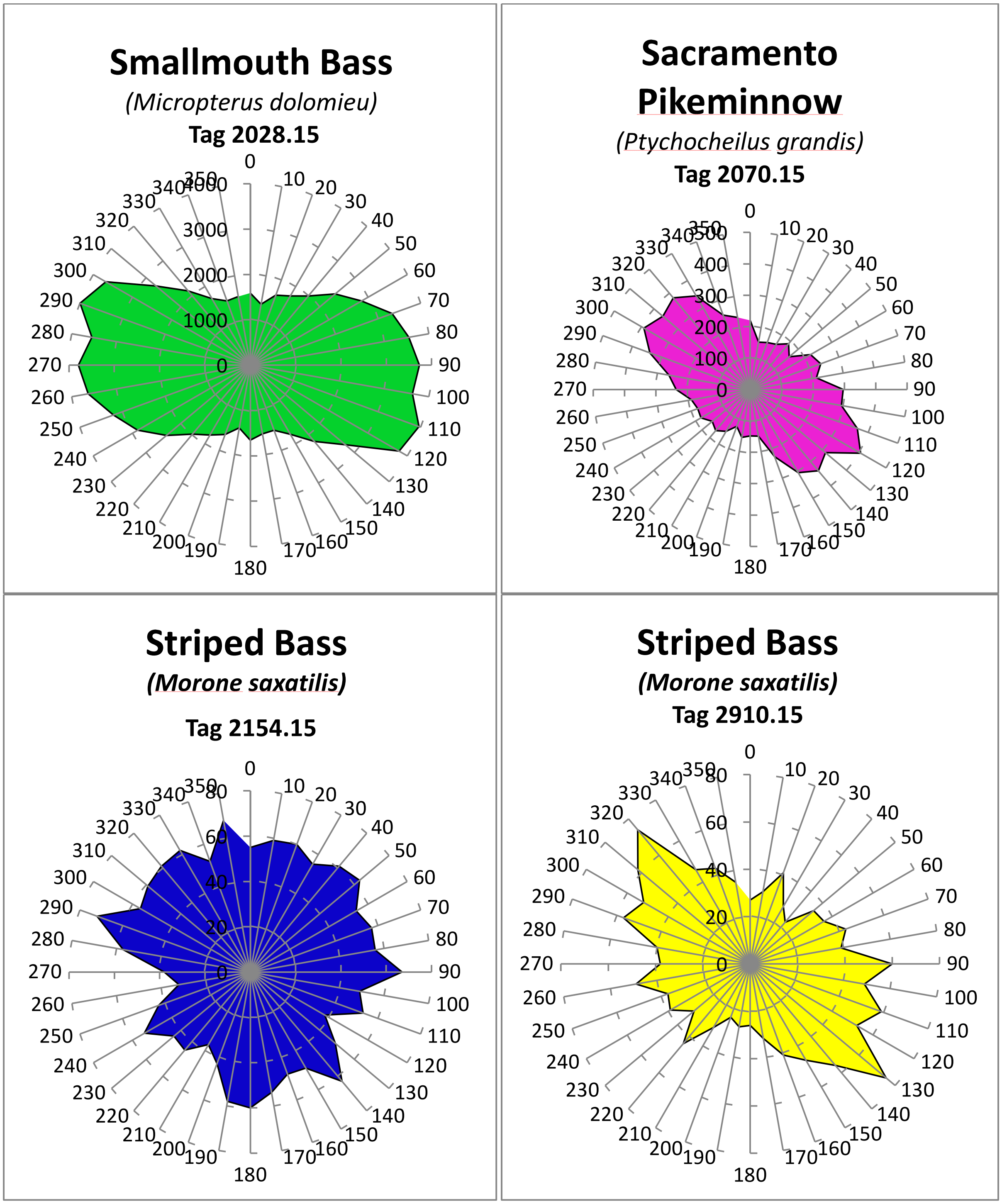


Figure 3.7-6 **Radar Plots of Direction of Travel for Four Tagged Predatory Fish, Georgiana Slough, Spring 2012**

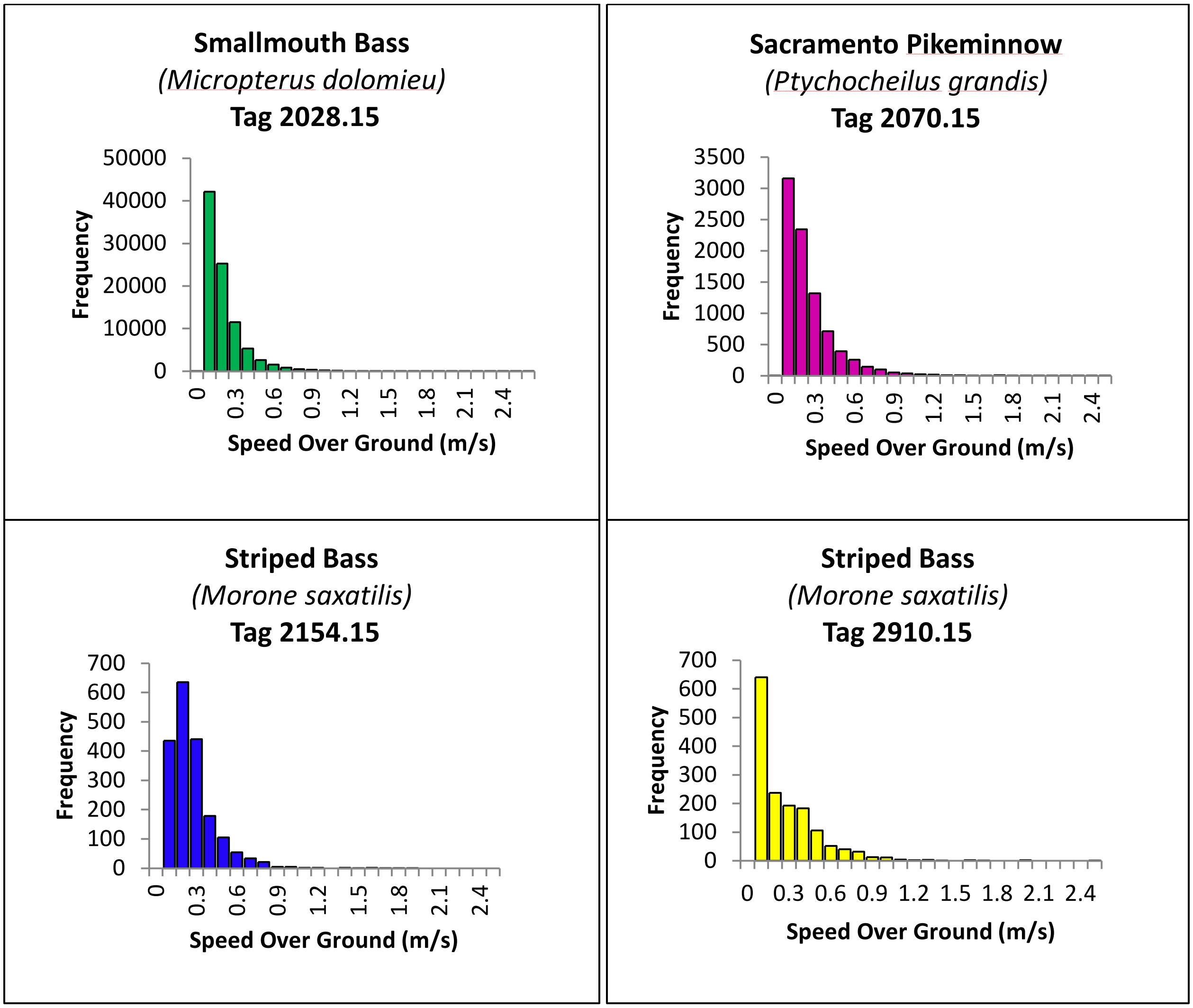


Figure 3.7-7 **Frequency Histograms of Speed over Ground for Four Tagged Predatory Fish, Georgiana Slough, Spring 2012**

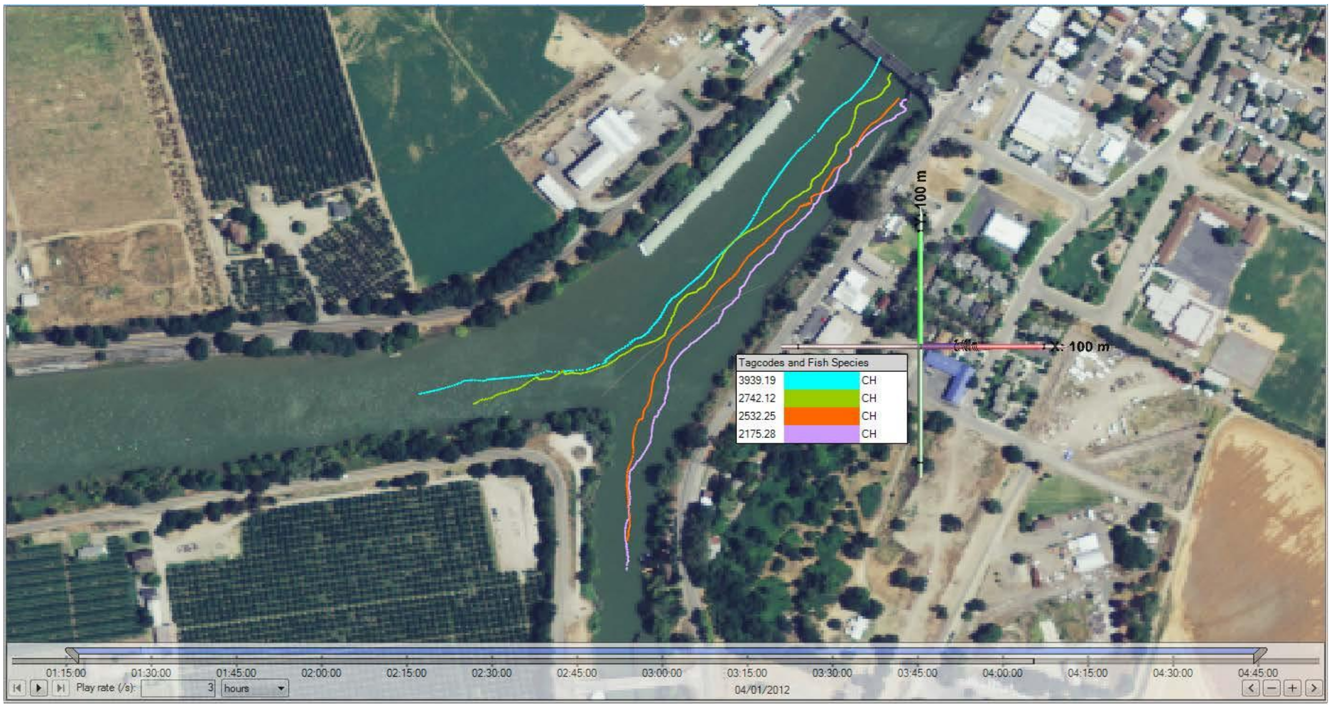


Figure 3.7-8 Tracks of Four Tagged Chinook Salmon, Georgiana Slough, Spring 2012

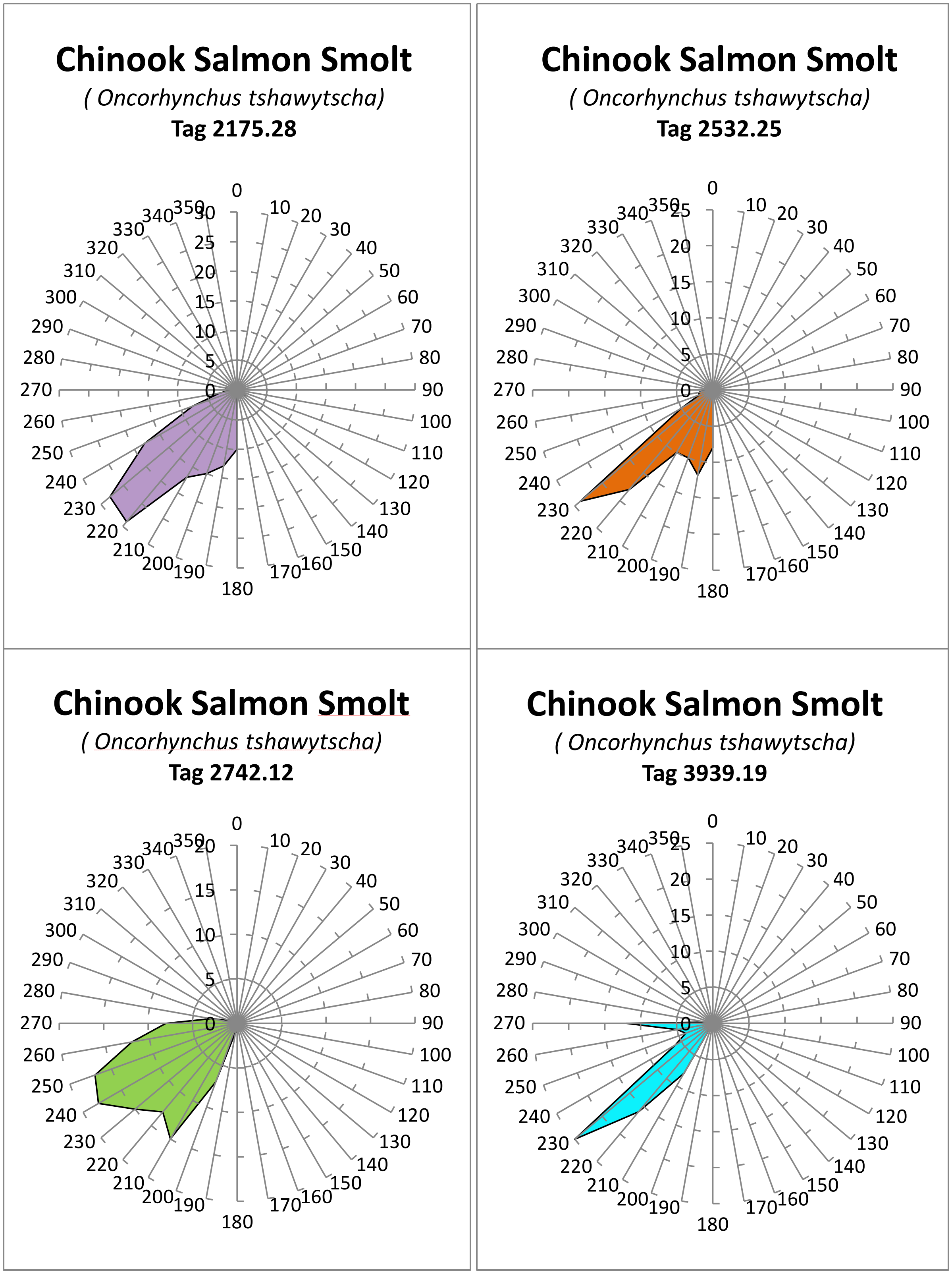


Figure 3.7-9 **Radar Plots of Direction of Travel for Four Tagged Chinook Salmon, Georgiana Slough, Spring 2012**

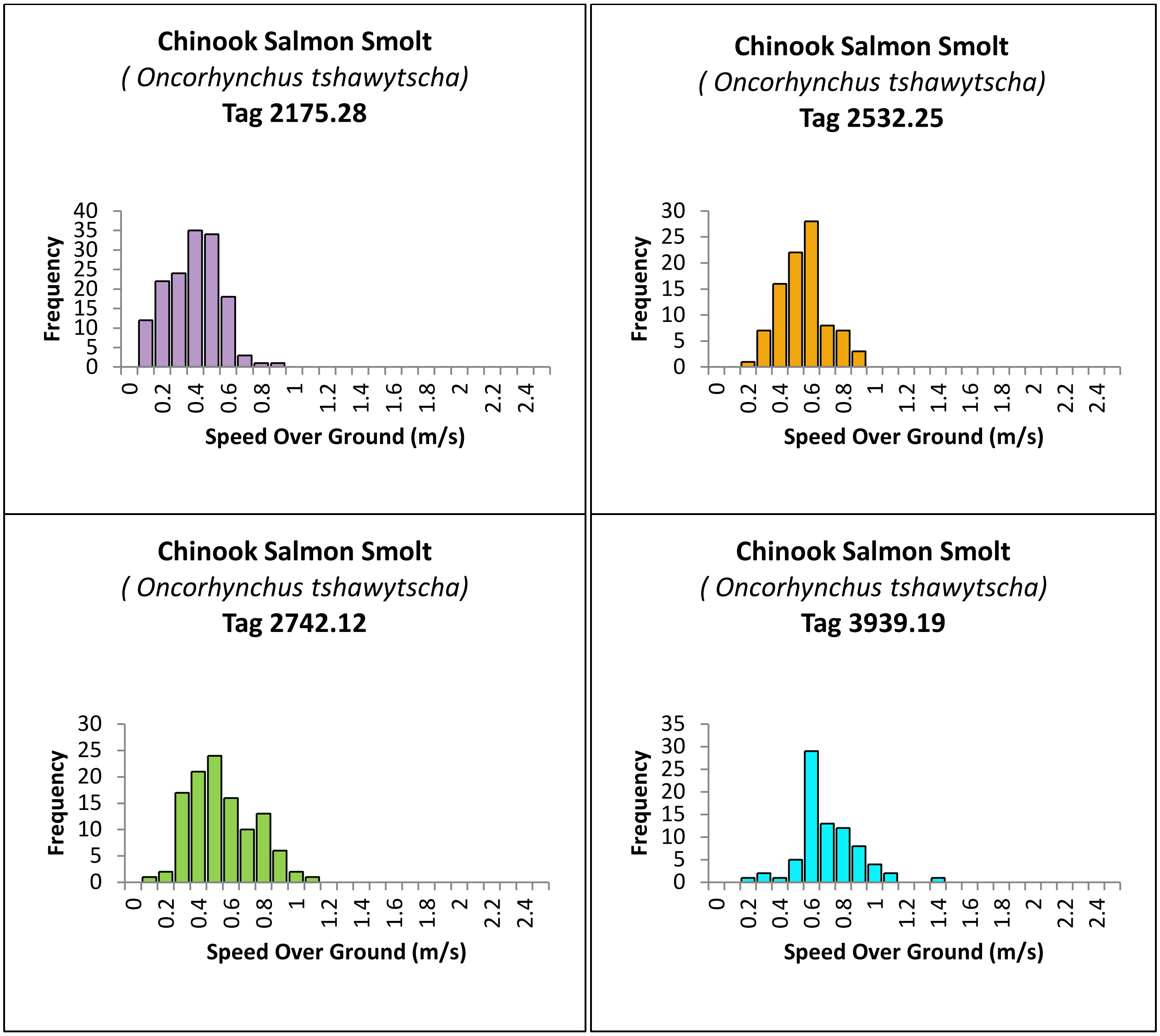
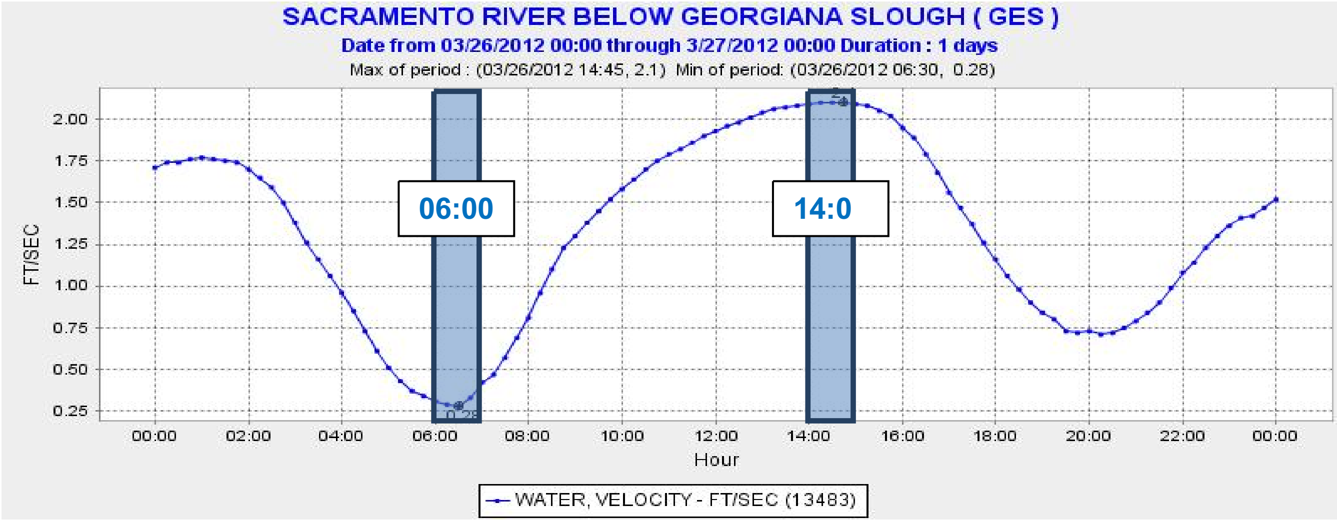
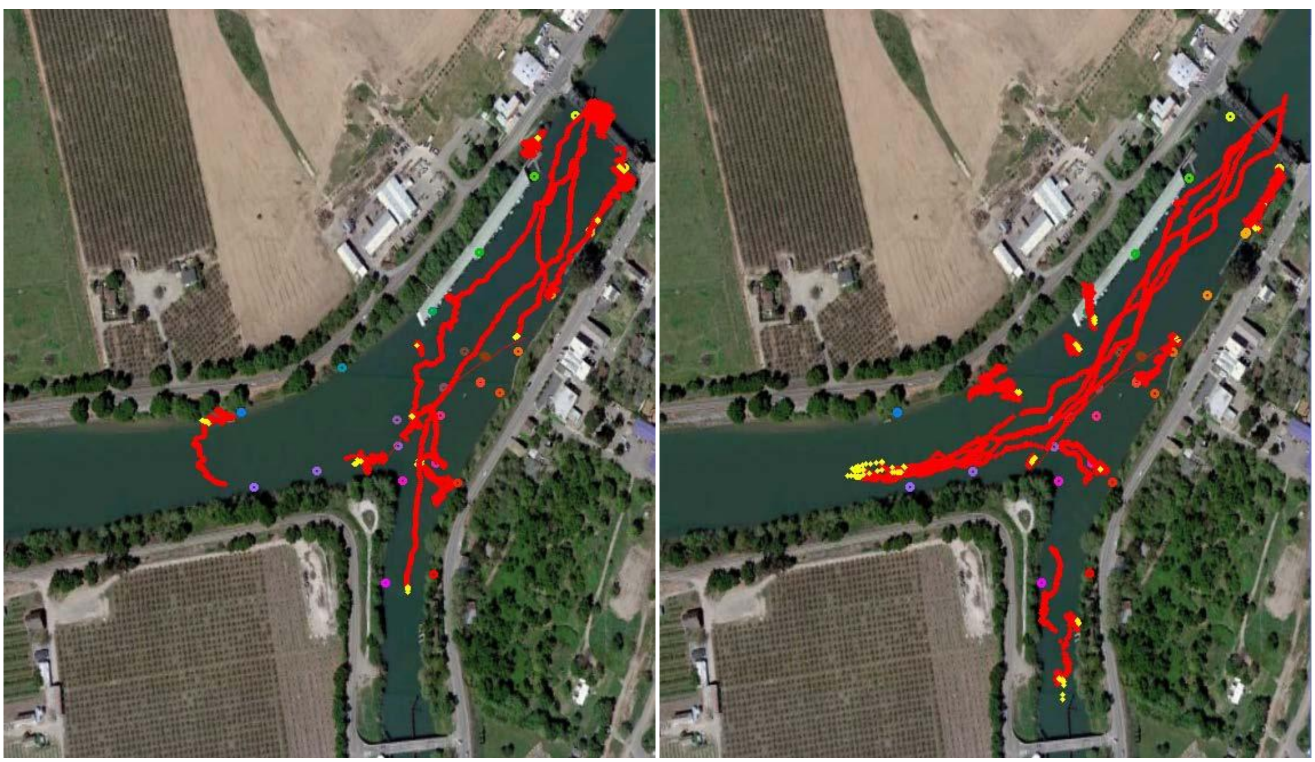


Figure 3.7-10 **Frequency Histograms of Speed over Ground for Four Tagged Predatory Fish, Georgiana Slough, Spring 2012**



Source: California Department of Water Resources, California Data Exchange Center

Figure 3.7-11 Water Velocity for the Sacramento River during Selected Hours on March 26, 2012



Note: Comparison of predator tracks and salmonid tracks during low- (left) and high-velocity (right) conditions.

Figure 3.7-12 Tracks of All Selected Tagged Fish on March 26, 2012, 06:00 to 07:00 (Left) and 14:00 to 15:00 (Right), Georgiana Slough

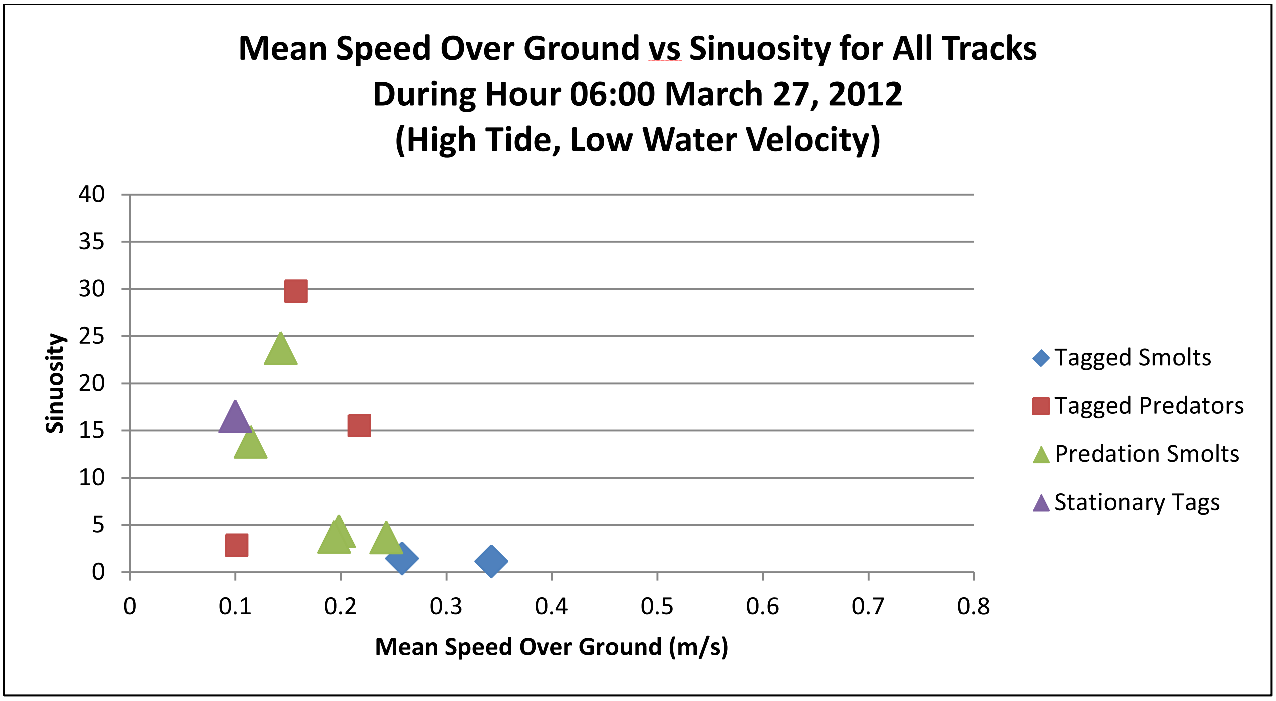


Figure 3.7-13 Mean Speed over Ground and Sinuosity for All Selected Tagged Fish in the Array during High Tide, Low-Water-Velocity Conditions for 06:00 to 07:00, March 26, 2012

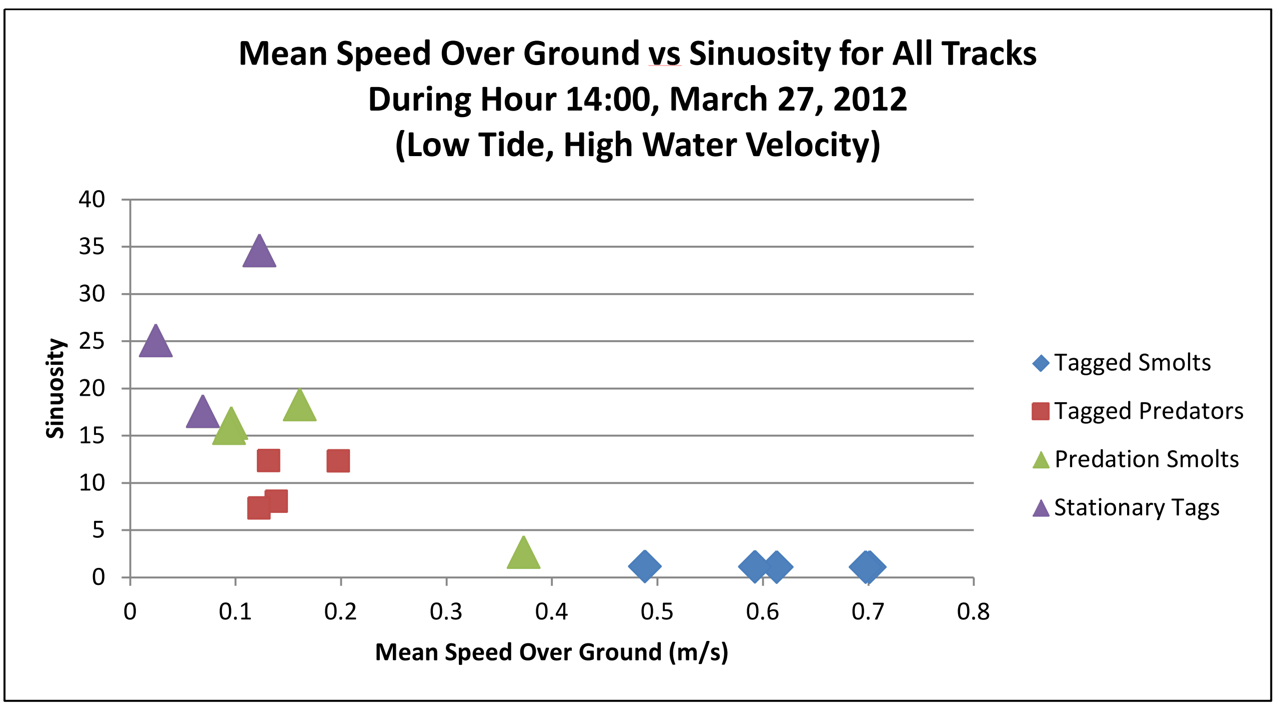
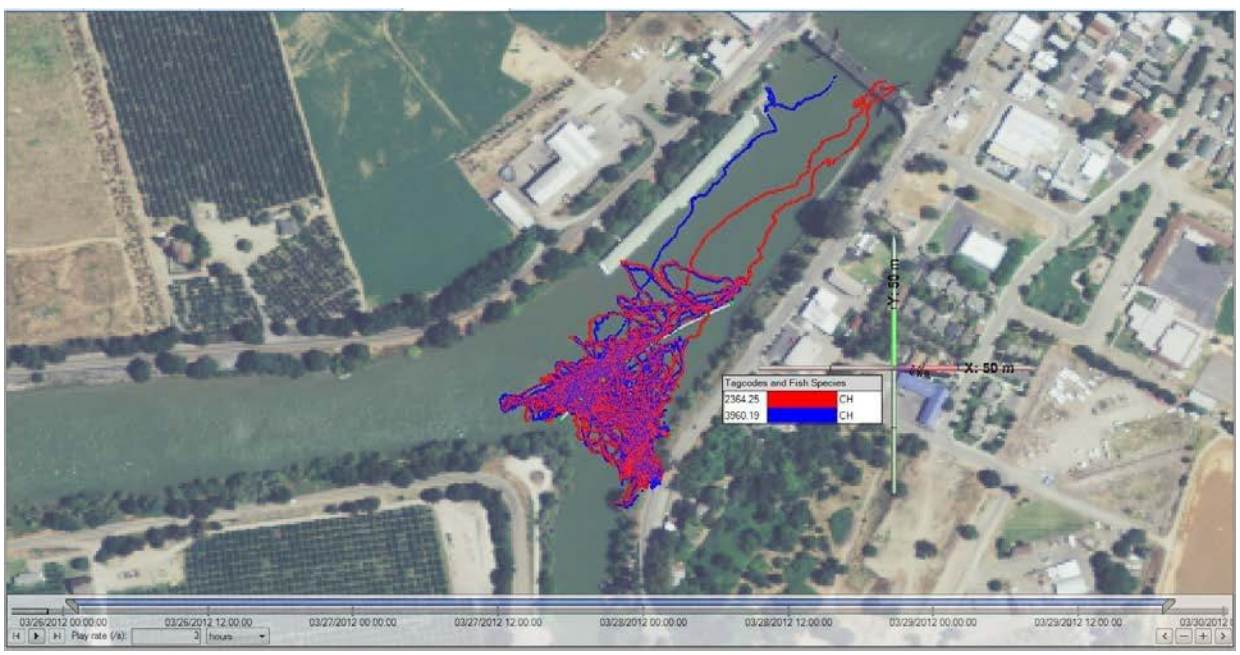


Figure 3.7-14 Mean Speed over Ground and Sinuosity for All Selected Tagged Fish in the Array during Low Tide, High-Water-Velocity Conditions for 06:00 to 07:00, March 26, 2012

Although fish may remain in one location continuously for relatively long periods, the sudden change from even a slightly moving tag to a completely stationary tag is evident in the time-correlated display of single or multiple hydrophone data (**Figure 3.7-16**). Four additional defecation events are shown on **Figure 3.7-17**. Stationary tags are clear indications of defecation events by predators that have preyed on tagged salmonids and are resident in or passing through the study array.

Although tagged salmonids showed clear increases in mean speed over ground during the high-flow period, the sinuosity values remained low during high- and low-water-velocity periods. Tagged predators showed higher sinuosity values for both flow conditions but relatively low and constant mean speed over ground values for both flow periods. Tagged salmonids classified as having been eaten by a predator had speed over ground and sinuosity values more closely matching those of tagged predators. Stationary tags (salmonid tags presumably defecated by a predator) show some sinuosity and speed over ground values because of positioning error.

Sound pulses from acoustic tags easily pass through a fish's body wall, even if a smaller tagged fish is eaten by a larger fish. To correctly interpret acoustic tag data, it is important to recognize when a predation event has occurred (Vogel 2011). If the acoustic tags have short, precisely controlled transmission intervals, have detection and ID ranges that are the same, and are detected on multiple hydrophones at once, then accurate tracks of individual fish can be generated (Ehrenberg and Steig 2009). Tracks of two tagged salmonids that overlap in space and time (salmonids appear to swim together) may indicate that a predator has eaten two tagged salmonids. Another possibility is that the tagged salmonids are exhibiting schooling behavior. **Figure 3.7-15** shows an example of a likely predation event because (1) the two tags have continuously overlapping tracks for over 3 days, and (2) one of the tags became completely stationary (presumably defecated) in the array and remained stationary until the end of the tag battery life.



Note: The tagged fish entered the array individually from upstream. They begin swimming simultaneously at 3:19:40 on March 26 and continued for more than 3 days. Tag 3960.19 was shed at 7:45:51 on March 29. Tag 2364.25 left the study array, traveling back upstream.

Figure 3.7-15 Tracks of Two Chinook Salmon Tags (2364.25, Red Spheres, and 3690.19, Blue Spheres)

Although fish may remain in one location continuously for relatively long periods, the sudden change from even a slightly moving tag to a completely stationary tag is evident in the time-correlated display of single or multiple hydrophone data (**Figure 3.7-16**). Four additional defecation events are shown on **Figure 3.7-17**. Stationary tags are clear indications of defecation events by predators that have preyed on tagged salmonids and are resident in or passing through the study array.

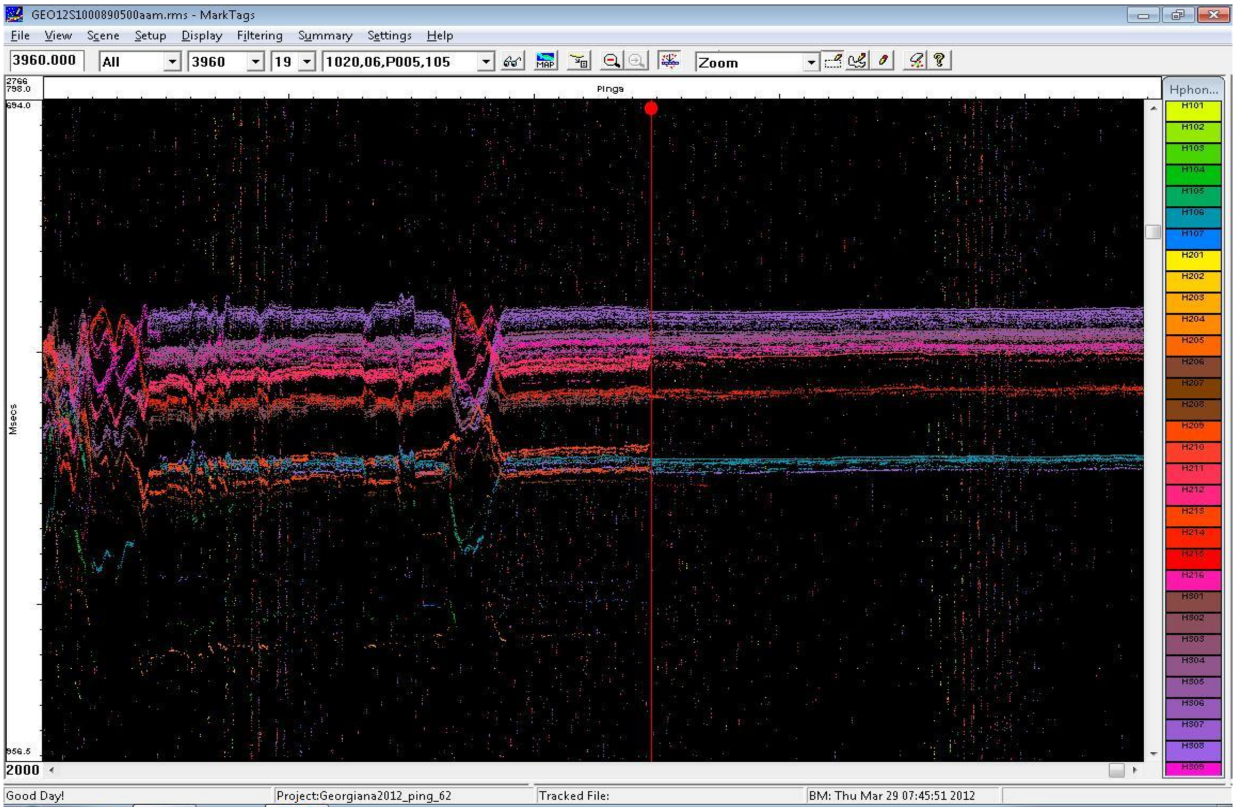


Figure 3.7-16 Raw Detection Data from Chinook Salmon Tag 3690.19 on March 29, 2012, 05:00 to 10:00, Indicating a Moving Tag (Left of Red Line) to a Stationary (Defecated) Tag (Right of Red Line)

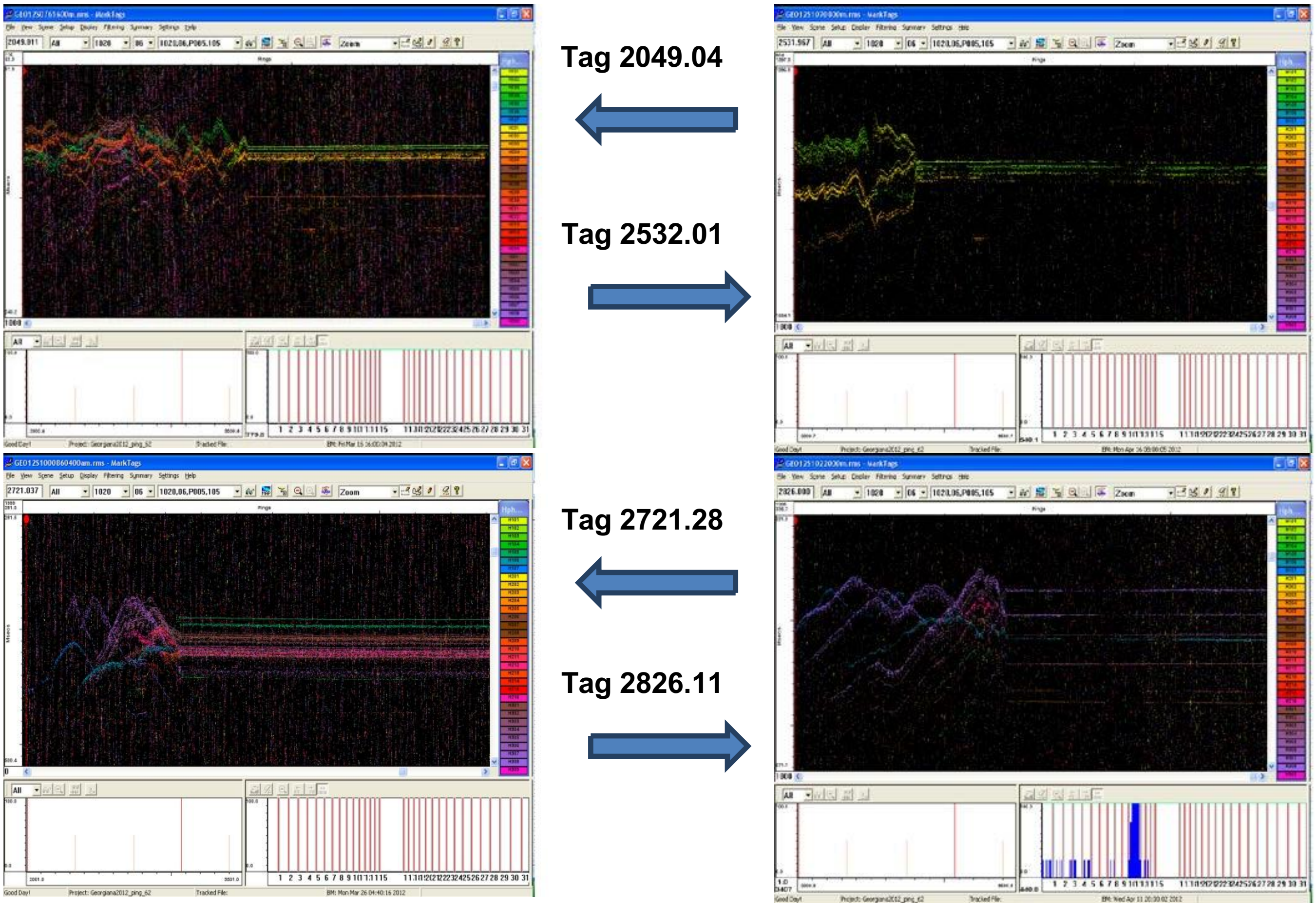


Figure 3.7-17 **Raw Detection Data from Four Additional Chinook Salmon Tags, Indicating Defecation Events**

3.7.3 SPATIAL ANALYSIS OF TAGGED PREDATORS AND PREDATION EVENTS

METHODS

Methodologies were designed to address the objectives of the 2012 GSNPB predatory fish analysis. Predatory fish habitat use, behavior, and predation frequency data were collected to answer the following questions:

1. How do predatory fish use available habitat in the study area?
2. Does installation of a BAFF increase predatory fish densities in the immediate area?
3. What effect do BAFF operations have on the distribution of predatory fish in the immediate area?
4. Do predatory fish become conditioned to the BAFF through time?
5. Does the BAFF's operation result in increased predation rates of juvenile salmonids?

To answer these questions, the predator track analyses were divided into two general topics. The first involved developing habitat polygons (river margin vs. open water) throughout the study area, and the second involved developing spatial polygons around the BAFF. For each pathway, the amount of time predators spent in each polygon was quantified. Quantifying occupation time provided information on predator use by habitat type and by BAFF proximity in association with BAFF operations.

Occupation time and habitat use for the habitat polygons and the BAFF spatial polygons were compared for the following BAFF conditions: BAFF On vs. BAFF Off, and BAFF installed vs. BAFF not installed.

Habitat Polygons

The study area was divided into two broad habitat polygon types, river margin and open water, to determine predator location and habitat use in the study area. The landside boundary for each river margin polygon was defined by the normal high-water mark. The normal high-water mark was adapted from California Department of Fish and Wildlife (DFW [DFG] 2007) because formal delineation was not available for the study area. The normal high-water mark delineated was adjusted using National Agriculture Imagery Program (FSA 2012) imagery and HTI fish locations to best reflect the normal high-water mark during the study time period. The waterside boundary for each river margin habitat polygon was defined by the waterside boundary of any hard structure (i.e., docks) located along the shoreline and extending into the river or by the 14-foot (4.3-m) depth contour of the river, whichever was greatest (**Figure 3.7-18**). The approximate 4.3-meter depth contour was chosen because the nearshore shelf area begins sloping into the river basin at a depth of approximately 4.3 m. The habitat type of the landside boundary was used to describe each river margin habitat polygon which included riprap, mud bank, mud flat, and dock. The open water habitat polygon consisted of one polygon and included all waters in the study area not included in a river margin habitat polygon.

BAFF Spatial Polygons

The area adjacent to the BAFF was delineated into three spatial polygons to determine whether predator use differed among spatial scales in association with BAFF operations. Predator occupation time was quantified in spatial polygons around the BAFF at distances of 0-5 m, 540 m, and 40-80 m.

Occupation Time Metric

Occupation time in seconds was determined for each polygon and normalized to meters squared (m^2) to account for size differences among polygons. The data were normalized again to account for differences in the number of tagged predatory fish using the study area among BAFF conditions and among time periods of interest. This allowed comparisons between and among BAFF conditions and time periods. The resulting metric is expressed as a percentage of total occupation time, also referred to as occupation rate, and was calculated by dividing a polygon's occupation time by the sum of occupation times for all polygons in the BAFF condition or time period of interest. For example, to determine the percentage of total occupation time, or occupation rate normalized to area, in dock habitat polygons when the BAFF was on, occupation time in dock habitat polygons when the BAFF was on (seconds per meter squared [sec/m^2]) was divided by the sum of occupation times for all five habitat polygon types (riprap, mud bank, open water, mud flat, and dock) when the BAFF was on (sec/m^2) and expressed as a percentage.

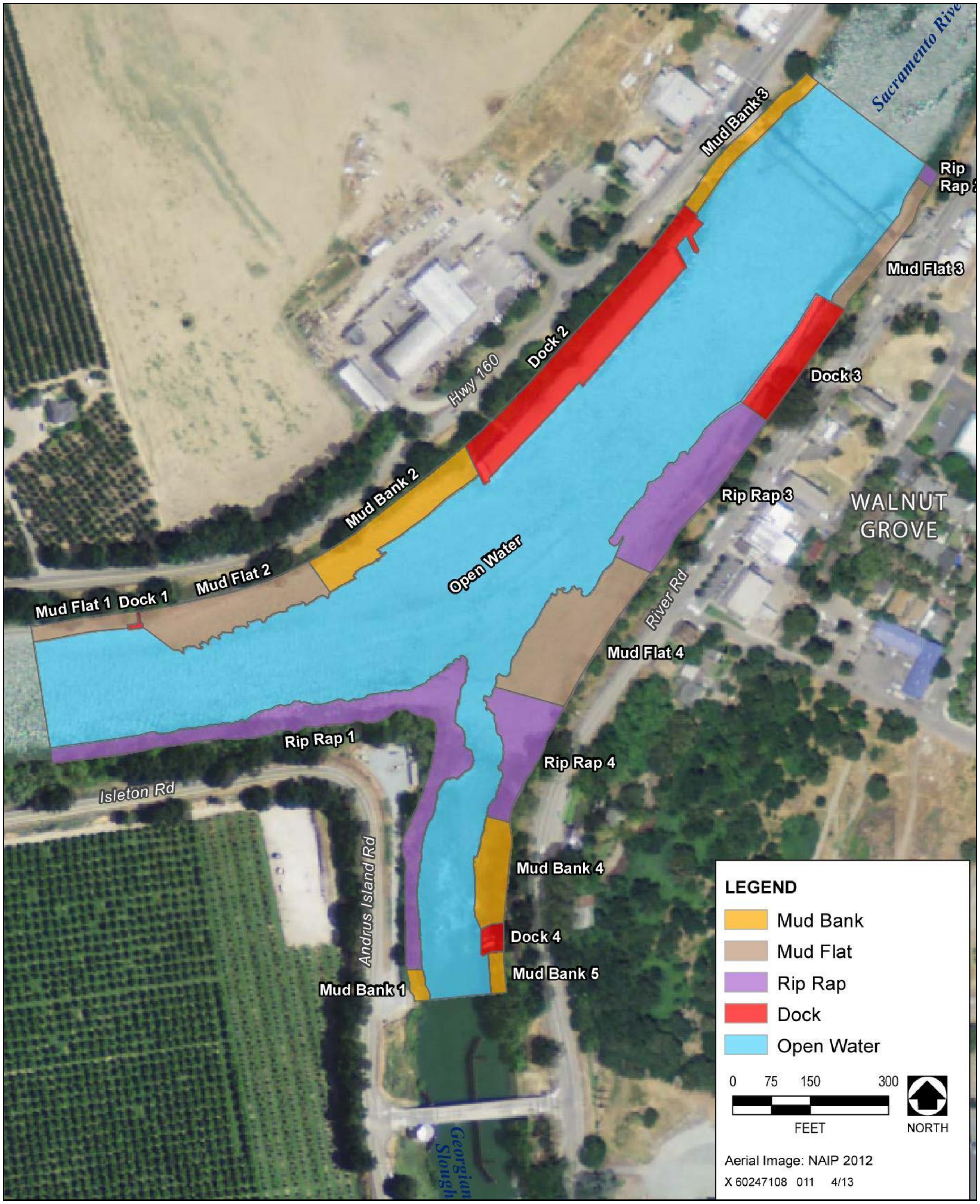


Figure 3.7-18 **River Margin Habitat Polygons with a Waterside Boundary Defined by the 14-Foot Depth Contour**

Percent total occupation time was used to express occupation time in the habitat and spatial polygons during three discrete BAFF conditions. The first condition was defined as BAFF On/Off and includes dates and times from when the BAFF was first operational through when it was turned off for the last time. The second condition was defined as BAFF installed/not installed and included dates and times from when the BAFF was installed through when the BAFF was removed. The third condition is defined as BAFF On and included only those dates and times when the BAFF's deterrence features were operational. For this analysis, the BAFF On period was blocked into three approximately equal periods.

Study Area Boundary and Time Period Definitions

Predatory fish tags were detected from approximately about 45 m upstream of the Walnut Grove Bridge to about 70 m downstream of the most downstream hydrophones in both the Sacramento River and Georgiana Slough. Therefore, the habitat and spatial polygons were bounded by these borders (**Figure 3.7-18**).

The BAFF was first turned on at 13:40 on March 6, 2012, at the beginning of the 25-hour on/off operational cycle. It was turned off for the last time at 02:05 on April 29, 2012, marking the end of the operational time period. The first tagged predator was released in the study area at 10:49 on February 26, 2012, and the first BAFF pile was placed into the river on February 14, 2012. The last BAFF pile was removed from the river at 17:00 on May 10, 2012, and the study array stopped collecting data at 07:59 on May 29, 2012. Following is a summary of each BAFF condition and associated time period:

BAFF Installed:	February 26 at 10:49 through May 10 at 17:00
BAFF Operation (On/Off time blocks):	March 6 at 13:40 through April 29 at 02:05
BAFF Not installed:	May 10 at 17:01 through May 29 at 07:59

Analyses

This section describes how the analyses addressed each objective of the 2012 GSNPB predatory fish analyses. Comparisons for each objective were made by individual species and with the data pooled across all species. Fish behavior, including predation rates, is influenced by a multitude of environmental variables, including water temperature, turbidity, flow, day/night period, tide phase, and ambient light. The predatory fish analyses addressed only potential effects from the BAFF's deterrence and structural features on fish behavior and predation rates and did not address potential effects from environmental variables.

RESULTS

Overview of Predators Captured and Tagged

Predator Catch Characteristics

Sample dates were generally evenly spaced throughout the study period. However, storms and other environmental conditions caused high and turbid flows, low water temperatures, and unsafe conditions prevented sampling during certain periods. The first predator was captured on February 26, 2012, and the last sample day was May 17, 2012. Sampling occurred on 15 separate days. A total of 125 predatory fish were captured, 50 of which were tagged. One hundred of the 125 captures (80 percent) were caught in the study area, and the remaining 25 captures (20 percent) were caught outside of the study area but within a 1-mile radius of the study area boundary. Forty-two of the tagged fish were caught in the study area (84 percent). The species captured were spotted bass, smallmouth bass, largemouth bass, striped bass, Sacramento pikeminnow, and white catfish (*Ameiurus catus*). Striped bass were captured and tagged most frequently, and largemouth bass were captured least frequently. Largemouth bass and white catfish were not tagged (**Table 3.7-5**).

Table 3.7-5
Length and Weight Range and Length and Weight Average by Species of Predators Captured and Tagged

Species	Captures	Minimum Length (mm)	Maximum Length (mm)	Average Length (mm)	Minimum Weight (g)	Maximum Weight (g)	Average Weight (g)
Sacramento pikeminnow	1	587	587	587	1,882	1,882	1,882
Striped bass	29	366	610	481	454	2,858	1,236
Smallmouth bass	14	309	408	342	272	975	543
Spotted bass	6	322	400	369	431	1,089	767
Tagged captures	**50**	**309**	**610**	**430**	**272**	**2,858**	**998**

Micropterus Hybridization in the Study Area

The study area location is unique to the Delta in terms of *Micropterus* species presence because all four species are present. Smallmouth bass and spotted bass are common throughout the north Delta, largemouth bass are found throughout the Delta, and redeye bass are present in the area presumably from a source population in the Cosumnes River. *Micropterus* species readily hybridize, and many fish captured during our study appeared to be hybrids based on morphological characteristics. A percentage of the captured smallmouth and spotted bass were noted on datasheets as appearing to be hybrids but were recorded to species based on subjective interpretation of what species they most resembled. Smallmouth bass and spotted bass hybridize most frequently among *Micropterus* species, resulting in what is referred to as a "meanmouth" or "mulie bass", and this was the most common hybrid type observed in the capture sample. Hybrids having largemouth bass morphological characteristics were not observed during the study. Redeye bass morphological characteristics were observed in several captures that were noted as appearing to be hybrids. One pure strain redeye bass was captured near the end of the study period, close to the DCC gates; the gates had been opened several days previously. This fish was not recorded on datasheets because sampling had ended for the day and capture crews were searching the DCC for an influx of predators resulting from opening of the gates. Difficulties associated with identifying apparent hybrids in the field coupled with subjective identification to species may have influenced the study's tagged predator proportions.

Tagged Predator Capture Results

Fifty predators were captured, tagged, and released into the study area. The furthest distance from the study area that a fish was captured and subsequently tagged was approximately 0.85 mile downstream in Georgiana Slough.

Efforts were made to tag a target proportion for each species (**Table 3.7-6**); however, the proportions were adjusted through time according to the catch proportions. Target and tagged proportions are shown in **Table 3.7-6**. The minimum target tagging proportion was not met for Sacramento pikeminnow, largemouth bass, and spotted bass. Sacramento pikeminnow and largemouth bass were the most difficult species to target and capture. Sacramento pikeminnow are likely present in the study area in greater numbers than captures suggest. However, angling techniques to target Sacramento pikeminnow were specific and did not capture other target species; therefore, specifically targeting Sacramento pikeminnow was an inefficient use of sampling time and was not conducted frequently. Six Sacramento pikeminnow were captured during the study, but only one was tagged because of the small size or condition of most of the fish. Based on primary sampling techniques and sampling effort, it is likely that few largemouth bass use the study area. One largemouth bass was captured; however, it was not tagged because of its small size. Tagged proportions for smallmouth bass slightly exceeded target proportions, and tagged proportions for striped bass slightly exceeded the maximum target proportion.

Table 3.7-6
Target and Tagged Predator Fish Species Proportions

	Sacramento Pikeminnow			Striped Bass			Largemouth Bass			Smallmouth Bass			Spotted Bass			Target Sample Size
	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	Min	Target	Max	
Target Proportions[1]	4% (2)	31% (15)	40% (20)	18% (9)	18% (9)	50% (25)	15% (7)	30% (15)	40% (20)	21% (11)	21% (11)	40% (20)	21% (11)	21% (11)	40% (20)	50
Tagged Proportions	2%			58%			0%			28%			12%			
Total	**1**			**29**			**0**			**14**			**6**			**50**

Note:

[1] Target proportions were based on sampling data collected by the California Department of Fish and Wildlife from 1995 through 1999 in Taylor Slough, Steamboat Slough, the Sacramento River at Threemile Island and at Paintersville, and the San Joaquin River at Bradford Island.

Recaptures

Three known recaptures of two tagged fish occurred. Both recaptured individuals had been implanted with an acoustic tag during the 2012 predator capture efforts. A spotted bass with tag code 2448.15 was first captured and tagged on February 26, 2012, when it measured 373 mm and weighed 794 grams. The first recapture of this individual occurred on April 14, 2012, when it measured 372 mm and weighed 816 grams. The second recapture of this individual occurred on May 5, 2012, when it measured 373 mm and weighed 771 grams. A smallmouth bass with tag code 2490.15 was first captured and tagged on March 10, 2012, when it measured 408 mm and weighed 975 grams. This individual was recaptured on March 25, 2012, when it measured 410 mm; weight was not recorded. Both individuals were immediately identified as recaptures based on visual observation of sutures. In all instances, the individuals and the sutures were in excellent condition.

Predator Tagging and the BAFF Operational Condition

Predator sampling occurred before, during and after the BAFF operational condition which ran from March 6, 2012 to April 29, 2012. This time period roughly corresponds with the Chinook salmon and steelhead release time periods which ran from March 6, 2012, and April 23, 2012. Twenty-five predators were captured, tagged, and released into the study area during the BAFF nonoperational time period, two before March 6 and 23 after

April 29. Predator species tagged and released in the study area before March 6 included smallmouth bass and spotted bass; smallmouth bass, striped bass, and spotted bass were tagged and released in the study area after April 29.

Acoustic Data Results and Discussion

Time Detected in Study Array

The amount of time each of the four tagged predator species was detected in the study array varied among species. The maximum amount of time each species could have been detected in the array (i.e., if every tagged fish stayed in the array from the time of its release through the end of acoustic data collection), the amount of time each species was detected in the array, and the percentage of maximum time each species was detected in the array are summarized in **Table 3.7-7**.

Table 3.7-7
Maximum Time Predatory Fish Could Have Been Detected in Study Array, Time Detected in Array, and Percentage of Maximum Amount of Time Each Species Was Detected in the Array

Species	Maximum Time Could Have Been Detected in Array (days)	Time Detected in Array (days)	Percentage of Maximum Time
Sacramento pikeminnow	79.6	2.1	2.61
Smallmouth bass	451.4	195.8	43.37
Spotted bass	320.0	211.1	65.97
Striped bass	1,433.5	37.5	2.61
Total	**2,284.5**	**446.4**	**19.54**

Different life history strategies, including spawning behavior and timing, likely accounted for differences among species in the amount of time detected in the study array. Sacramento pikeminnow are present in small numbers in the Delta; are most often associated with lotic habitats; and spawn in nontidal-freshwater systems, where they often complete their entire life cycle (Brown 1990; Moyle 2002; Nobriga and Feyrer 2007). However, high-flow events sometimes transport pikeminnow downstream from natal systems to the Delta, where they remain until they mature or until they migrate back upstream to spawn (Nobriga et al. 2006; Nobriga and Feyrer 2007). Spawning occurs from March through May. Pikeminnow spawning habitat is not present in the study area, and those pikeminnow in the study area during the study period may represent migrating individuals. One Sacramento pikeminnow was tagged and remained in the study area for a short period. The individual was last detected in the study area on March 22 at 13:20 at the most upstream peripheral hydrophone (**Figure 2-1**) in the Sacramento River. It was detected in another project's study area (approximately 8.4 km upstream) on March 23. The individual exited this study area after approximately 3 minutes, moving further upstream. The direct and rapid swim signature of this fish during the time it was detected was characteristic of migratory behavior, and this individual was likely en route to an upstream spawning area.

Striped bass are found throughout the Delta and, like Sacramento pikeminnow, spawn in upstream, nontidal-freshwater systems. Spawning primarily occurs from April through May. Because the study area lacked suitable spawning habitat, the striped bass tagged in the study area likely represented fish migrating to upstream spawning areas. The study area appears to be part of a migration corridor for Sacramento pikeminnow and striped bass (Moyle 2002; Vogel 2012). Neither species would be expected to have high site fidelity for, nor be detected for any substantial amount of time in, the study area (Moyle 2002; Vogel 2012).

Smallmouth and spotted bass have similar life histories, and both will undertake comparatively short migrations to search for seasonal habitat and spawning areas (Lyons and Kanehl 2002; Orth and Newcomb 2002). Spawning occurs across a wide range of habitat types, including tidally influenced areas; hard substrates lacking substantial sedimentation are optimal (Bozek et al. 2002; Moyle 2002). The timing of spawning is triggered by water temperature and length of photoperiod and can vary substantially (Gross et al. 2002); however, most spawning occurs between March and May (Moyle 2002). Smallmouth and spotted bass would be expected to spend much greater amounts of time in the study area during the study period than striped bass because: 1) both species are less migratory than striped bass (Lyons and Kanehl 2002; Orth and Newcomb 2002; Vogel 2012); 2) spawning had begun, spawning areas likely had been selected, and high site fidelity is typical during this period (Kubacki et al. 2002; Moyle 2002); and 3) most tagged individuals were captured in the study area and therefore would be expected to stay in the study area near spawning areas until the end of the spawn cycle (Kubacki et al. 2002).

How Do Predatory Fish Use Available Habitat in the Study Area?

Habitat Use: BAFF On vs. BAFF Off

Percent of the total occupation time for each habitat type, each species, and the BAFF On and BAFF Off conditions is shown in **Figure 3.7-19**. The single tagged Sacramento pikeminnow used dock habitat much more frequently than other habitat types during both BAFF conditions. However, dock habitat was used more when the BAFF was off (88 percent) compared to when it was on (63 percent). Open water and riprap habitat were used least frequently during both BAFF conditions. Dock, open water, and riprap were used more when the BAFF was off than when it was on.

Striped bass used dock habitat much more frequently than other habitat types during both BAFF conditions, but dock habitat was used most when the BAFF was on (69 percent) compared to when it was off (63 percent). Open water and mud bank were used least frequently during both BAFF conditions (> 3 percent); however, relative to other predator species, striped bass occupied open water habitat for a higher percentage of the time. All habitat types except riprap were used slightly more when the BAFF was on than when it was off. Habitat use characteristics generally were similar between BAFF conditions.

Smallmouth bass used dock and riprap habitat most frequently during both BAFF conditions. Dock habitat was used more when the BAFF was on (46 percent) than when it was off (13 percent), and riprap was used more frequently when the BAFF was off (64 percent) compared to when it was on (37 percent). Regardless of BAFF condition, smallmouth bass rarely occupied open water habitat (BAFF On 0.19 percent, BAFF Off 0.30 percent). All habitat types except dock were used more when the BAFF was off than when it was on. Habitat use generally differed between BAFF conditions; similarities included highest use of riprap and dock habitat and lowest use of open water.

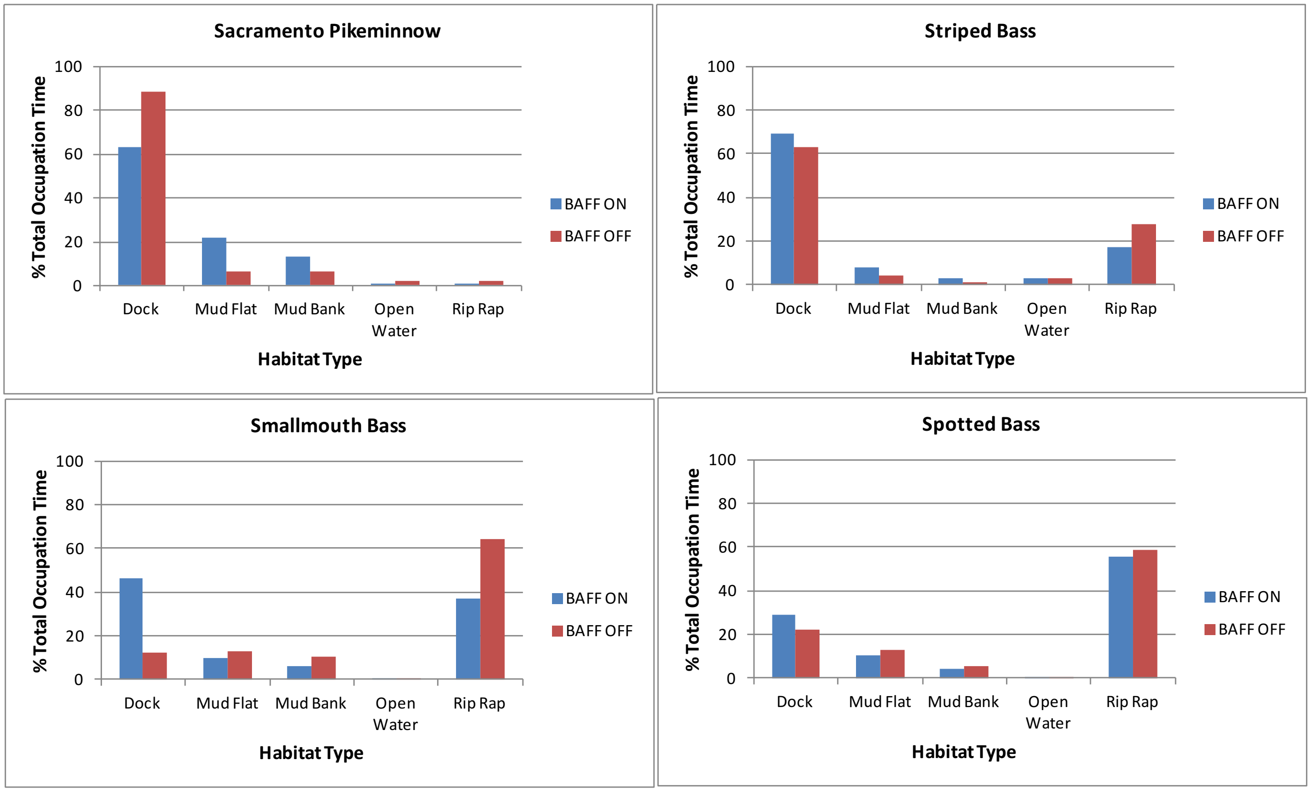


Figure 3.7-19 Percent of Total Occupation Time by Habitat for Each Species and for the BAFF On and BAFF Off Conditions

Spotted bass used riprap habitat much more frequently than other habitat types during both BAFF conditions (On 56 percent, Off 59 percent). Percent use of riprap habitat was nearly identical between BAFF conditions. Regardless of BAFF condition, spotted bass rarely occupied open water habitat (BAFF On 0.42 percent, BAFF Off 0.47 percent). All habitat types except dock were used more when the BAFF was off than when it was on. Habitat use was very similar between BAFF conditions.

All species used all habitat types during both BAFF conditions. Riprap and dock habitat were occupied most frequently among species and across BAFF conditions (**Figure 3.7-19**). The high use of riprap and dock habitat is typical for Sacramento pikeminnow, smallmouth bass, and spotted bass because these species tend to occupy the littoral zone; areas with high habitat complexity and some form of cover and structure are used most frequently (Moyle 2002). Striped bass is a pelagic species that often occupies open water habitat in search of schooling prey (Stevens 1966). However, striped bass tagged during the 2012 study did not show an affinity for open water habitat. Striped bass occupied dock and riprap habitat much more frequently and rarely occupied open water habitat. Most spawning in the Sacramento River occurs from Colusa to the mouth of the Feather River (Moyle 2002). Many striped bass move downstream to saline waters following the spring spawn (Moyle 2002). Acoustically tagged striped bass likely were individuals migrating to upstream spawning areas. High use of littoral habitat is atypical and may suggest that striped bass migrate along water course margins. Forty-one percent of tagged striped bass were detected approximately 8.4 km upstream of the study area in another project's study area (see **Appendix H**). The small amount of time striped bass were detected in the study array and the detection chronology, in terms of dates and movement direction, substantiates that the study area is primarily a migration corridor for striped bass.

The objective of the BAFF On/Off habitat comparison was to evaluate differences in predatory fish habitat use in the study area between the two BAFF conditions. With the exception of Sacramento pikeminnow, riprap (BAFF On 45 percent, BAFF Off 59 percent) and dock (BAFF On 39 percent, BAFF Off 20 percent) habitat were occupied most frequently regardless of BAFF condition (**Figure 3.7-20**). The small sample size for Sacramento pikeminnow may have masked typical habitat use for the species. In general, differences in habitat use between BAFF conditions were small. However, three clear patterns are shown for all species: 1) a higher use of riprap habitat when the BAFF is off compared to when it is on; 2) a higher use of dock habitat when the BAFF is on compared to when it is off; and 3) extremely low use of open water habitat (<1 percent) regardless of BAFF condition (**Figure 3.7-20**).

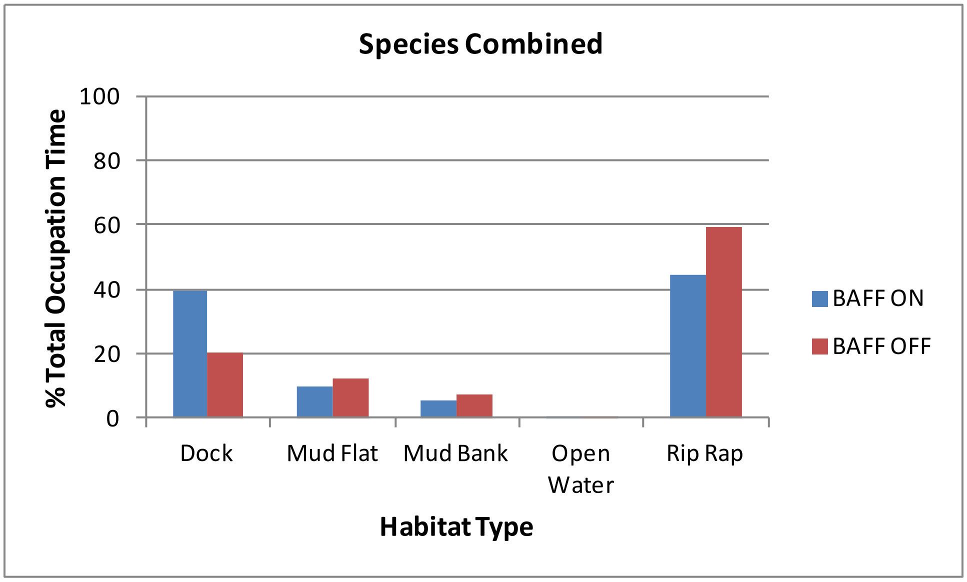


Figure 3.7-20 **Percent of Total Occupation Time by Habitat for Species Combined and for the BAFF On and BAFF Off Conditions**

It is interesting to note that the strongest habitat use patterns occurred in those habitats closest to the BAFF. Each end of the BAFF intersected the littoral zone in riprap habitat, and the middle section was in open water habitat. Thirty-two percent of the length of the BAFF was located in riprap habitat, and 68 percent was in open water habitat. A large dock habitat polygon was located just upstream of the northeastern terminus of the BAFF. These riprap and dock habitat polygons were found to hold a comparatively high number of predatory fish based on hook-and-line sampling efforts conducted during both the 2012 and the 2011 studies. Therefore, habitat use patterns in these polygons may reflect true responses to each BAFF condition because of: 1) their proximity to the BAFF; 2) the high number of fish using these polygons; and 3) the location of these polygons in relation to the effective range of the BAFF deterrence features.

Although the riprap habitat had high occupancy during both BAFF conditions, higher use occurred when the BAFF was off. The effective range of the BAFF deterrence features (sound) was about 80 m, and the riprap polygons with the highest occupancy rates were within this range. The dock habitat polygon with the highest occupancy rate was occupied more when the BAFF was on and was located just upstream of the high-use riprap polygon, and was located outside of the effective range of the BAFF deterrence features. This habitat use pattern, in conjunction with the BAFF On/Off operations, may suggest tagged predatory fish preferred to occupy riprap habitat; however, when the BAFF deterrence features were operational, some tagged fish were repelled away from the BAFF and sought refuge under the closest dock habitat. Lack of occupancy of open water habitat precludes elucidating differences in use between BAFF conditions but may suggest the BAFF does not increase predator densities in the immediate area.

Habitat Use: BAFF Installed vs. BAFF Not Installed

Percent of the total occupation time for each habitat type, each species, and the BAFF installed and BAFF not installed conditions is shown in **Figure 3.7-21**. Sacramento pikeminnow used dock habitat much more frequently (83 percent) than other habitat types during the BAFF installed condition. Habitat use data for Sacramento pikeminnow during the BAFF not installed condition do not exist because the only tagged individual exited the study area before the beginning of the not installed time period and did not return. The individual was last detected in the study area on March 22 at the most upstream peripheral hydrophone in the Sacramento River, moving upstream.

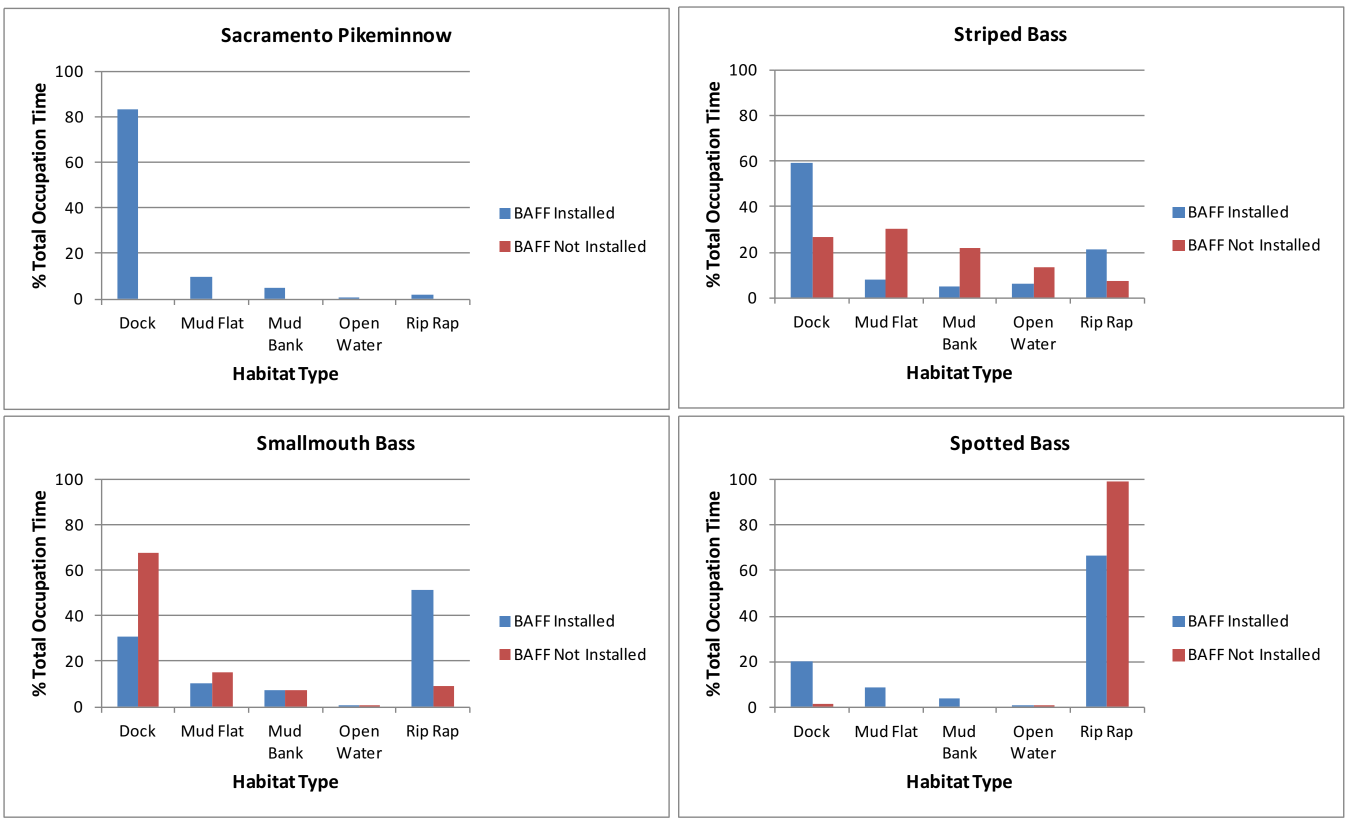


Figure 3.7-21 **Percent of Total Occupation Time by Habitat Type for Each Species and for the BAFF Installed and BAFF Not Installed Conditions**

Striped bass used dock and riprap habitat most frequently during the BAFF installed condition (59 percent and 21 percent, respectively) and mud flat and dock habitat most frequently during the BAFF not installed condition (31 percent and 26 percent, respectively). Mud bank and open water habitat were used least frequently during the BAFF installed condition (5 percent and 6 percent, respectively), and riprap and open water habitat was used least frequently during the BAFF not installed condition (7 percent and 14 percent, respectively). Habitat use was more evenly distributed among habitat types during the BAFF not installed condition than during the BAFF installed condition.

The objective of the BAFF installed/not installed habitat comparison was to evaluate differences in predatory fish habitat use in the study area between the two BAFF conditions. Among species, riprap and dock habitat were occupied most frequently during the BAFF installed condition (58 percent and 27 percent, respectively), and dock and mud flat habitat were occupied most frequently during the BAFF not installed condition (49 percent and 11 percent, respectively; **Figure 3.7-22**). A clear pattern of habitat use was evident among species (**Figure 3.7-22**); riprap and dock habitat received much greater use than the other habitats during both BAFF conditions. However, riprap habitat use was higher during the BAFF installed condition, and dock habitat use was higher during the BAFF not installed condition.

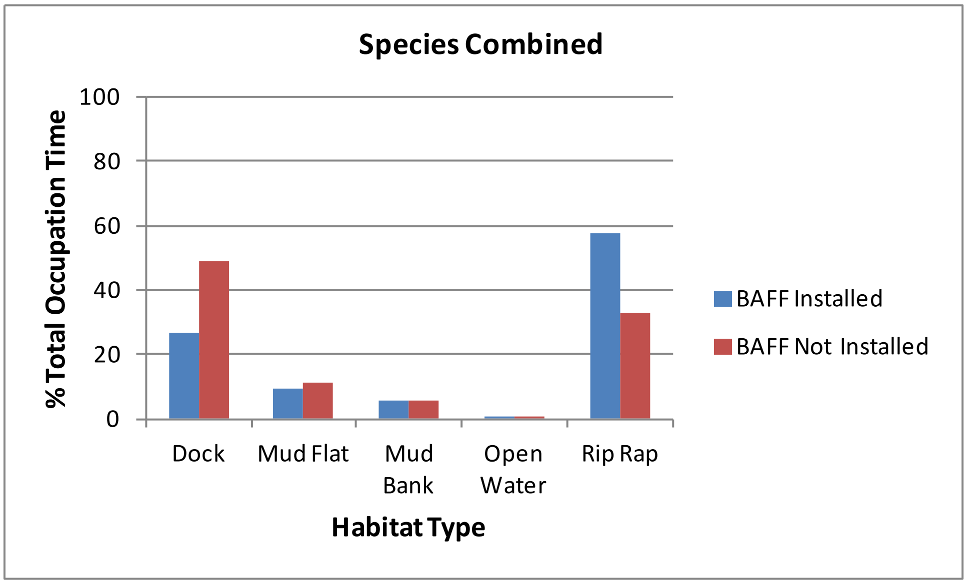


Figure 3.7-22 **Percent of Total Occupation Time by Habitat for Species Combined and for the BAFF Installed and BAFF Not Installed Conditions**

Riprap habitat was heavily used regardless of species or BAFF condition. The ends of the BAFF added structure and complexity to two large riprap habitat polygons, potentially increasing habitat value for predatory fishes, and may have contributed to the high use during the BAFF installed condition. Following removal of the BAFF structure, riprap habitat complexity decreased, potentially decreasing habitat value, and may have accounted for the higher use of dock habitat during the BAFF not installed condition. Dock habitat provides structure and has high habitat complexity for predatory fishes.

Open water habitat was rarely occupied during either BAFF condition, and differences in use between conditions were small (<1 percent). Low occupation of open water habitat regardless of BAFF condition and small differences in use between conditions may suggest that the addition of physical structures did not make open water habitat more attractive to predatory fish. In addition, occupation patterns between riprap and open water habitat and between the BAFF conditions may suggest the addition of physical structures influences predatory fish habitat selection in the littoral zone.

Does Installation of a BAFF Increase Predatory Fish Densities in the Immediate Area?

Percent of the total occupation time for each spatial polygon, each species, and the BAFF installed and BAFF not installed conditions is shown in **Figure 3.7-23**. Spatial polygon occupation data for Sacramento pikeminnow and the BAFF not installed condition do not exist because the only tagged individual exited the study area before the beginning of the not installed time period and did not return.

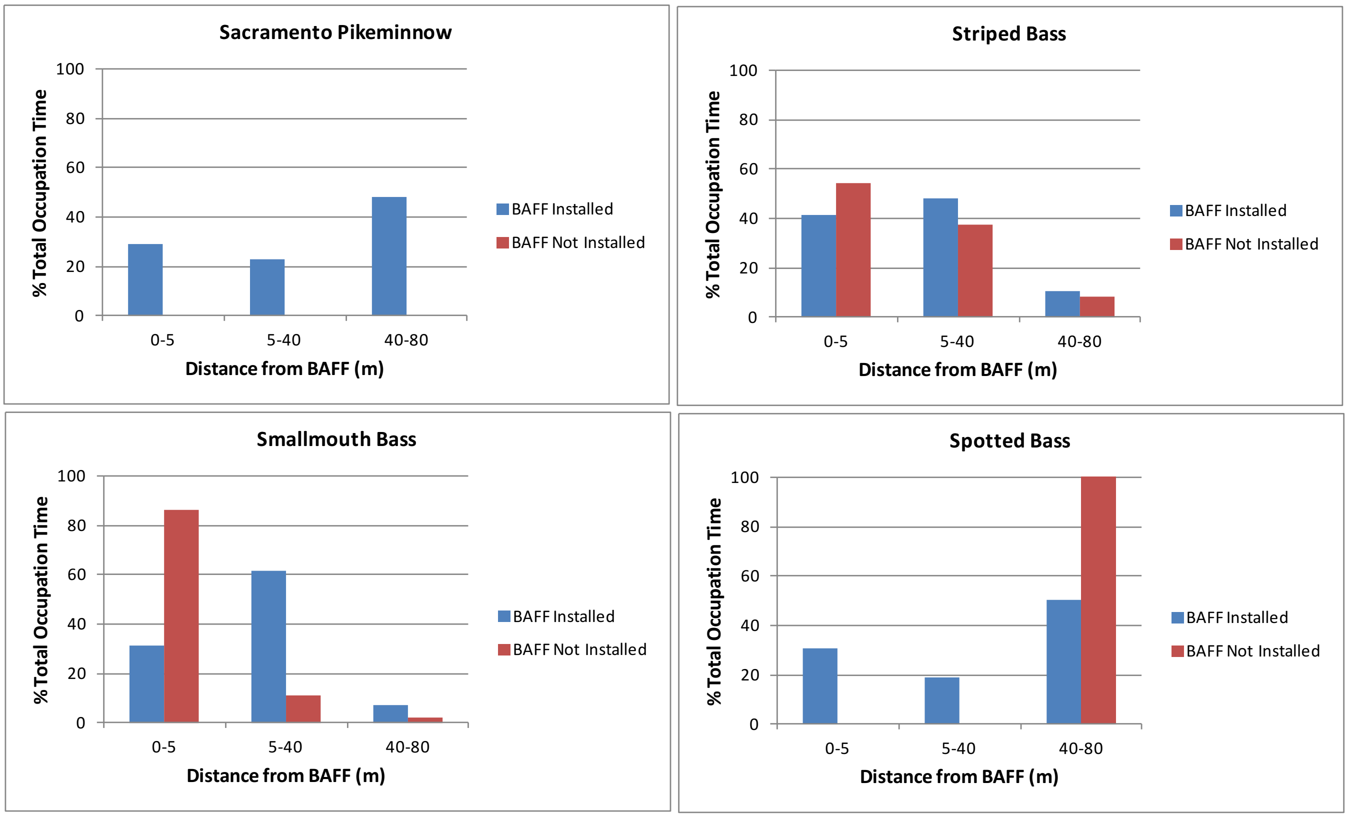


Figure 3.7-23 Percent of Total Occupation Time by Spatial Polygon for Each Species and for the BAFF Installed and BAFF Not Installed Conditions

The objective of the BAFF installed/not installed spatial comparison was to evaluate whether installation of structural features attracted predatory fish and increased densities in the area immediately surrounding the BAFF. Use of the spatial polygons during the BAFF not installed time period characterized baseline conditions against which BAFF installed use was compared.

Striped and spotted bass occupied the 0- to 5-m polygon most during the BAFF not installed condition and the 5- to 40-m polygon most during the BAFF installed condition. This occupation pattern was similar between conditions, suggesting that the BAFF's structural features had little effect on striped and spotted bass densities in the area immediately surrounding the BAFF. Operation of the BAFF's deterrence features may account for the higher use of the 5- to 40-m polygon during the BAFF installed condition and may suggest that striped and spotted bass showed some level of avoidance behavior in response to the BAFF's deterrence features.

Spotted bass occupied the 40- to 80-m polygon much more frequently than the other polygons during both BAFF conditions. However, the 0- to 5-m polygon and the 5- to 40-m polygon were occupied only during the BAFF installed condition (collectively 50 percent of the time), with greater occupancy in the 0- to 5-m polygon (38 percent of the time), which may suggest that spotted bass were attracted to the BAFF's physical features.

Pooled data (**Figure 3.7-24**) suggest BAFF structural features had little effect on predator densities in the area immediately surrounding the BAFF because: 1) greatest occupancy occurred within 5 m of the BAFF during the BAFF not installed condition; 2) greatest occupancy occurred during the BAFF not installed condition in two of the three polygons; 3) occupancy rates between conditions within 40 m of the BAFF were very similar (73 percent installed and 72 percent not installed); and 4) occupancy rates between conditions within 40-80 m of the BAFF were very similar (27 percent installed and 28 percent not installed).

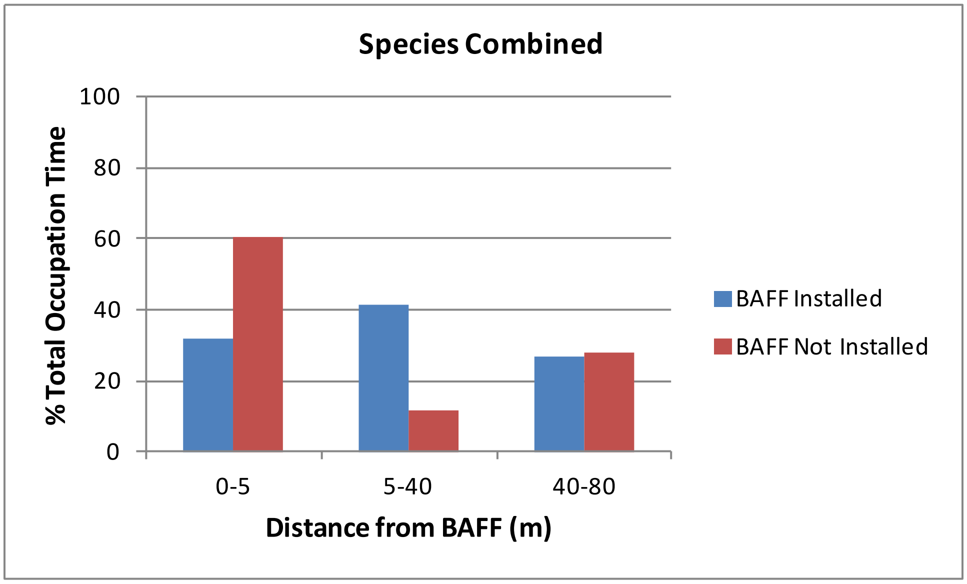


Figure 3.7-24 Percent of Total Occupation Time by Spatial Polygon for Species Combined and for the BAFF Installed and BAFF Not Installed Conditions

The predatory fish occupancy rate within 80 m of the BAFF was compared to the occupancy rate more than 80 m from the BAFF to further evaluate potential effects of the BAFF's structural features on predator densities. Baseline conditions (BAFF not installed) showed substantially higher use within 80 m of the BAFF than outside 80 m (91 percent and 9 percent, respectively). The pattern was similar for the BAFF installed condition (98 percent and 2 percent, respectively) with an increase in occupancy rate of 7 percent within 80 m. When occupancy rates were combined for both BAFF conditions, the occupancy rate within 80 m was 93% and outside 80 m was 7 percent. These occupancy rate patterns suggest a higher degree of use of that portion of the study area within 80 m of the BAFF location by predatory fish regardless of the presence of the BAFF's physical features. The small differences in occupancy rates in each spatial scale and among the BAFF installed condition, BAFF not installed condition, and conditions combined suggest that the BAFF's physical features had no effect on predator densities in the area immediately surrounding (within 80 m of) the BAFF.

What Effect Does BAFF Operation Have on the Distribution of Predatory Fish in the Immediate Area?

Percent of the total occupation time for each spatial polygon, each species, and the BAFF On and BAFF Off condition is shown in **Figure 3.7-25**. Occupancy patterns suggest a positive relationship between occupancy rate and the distance from the barrier during the BAFF On condition.

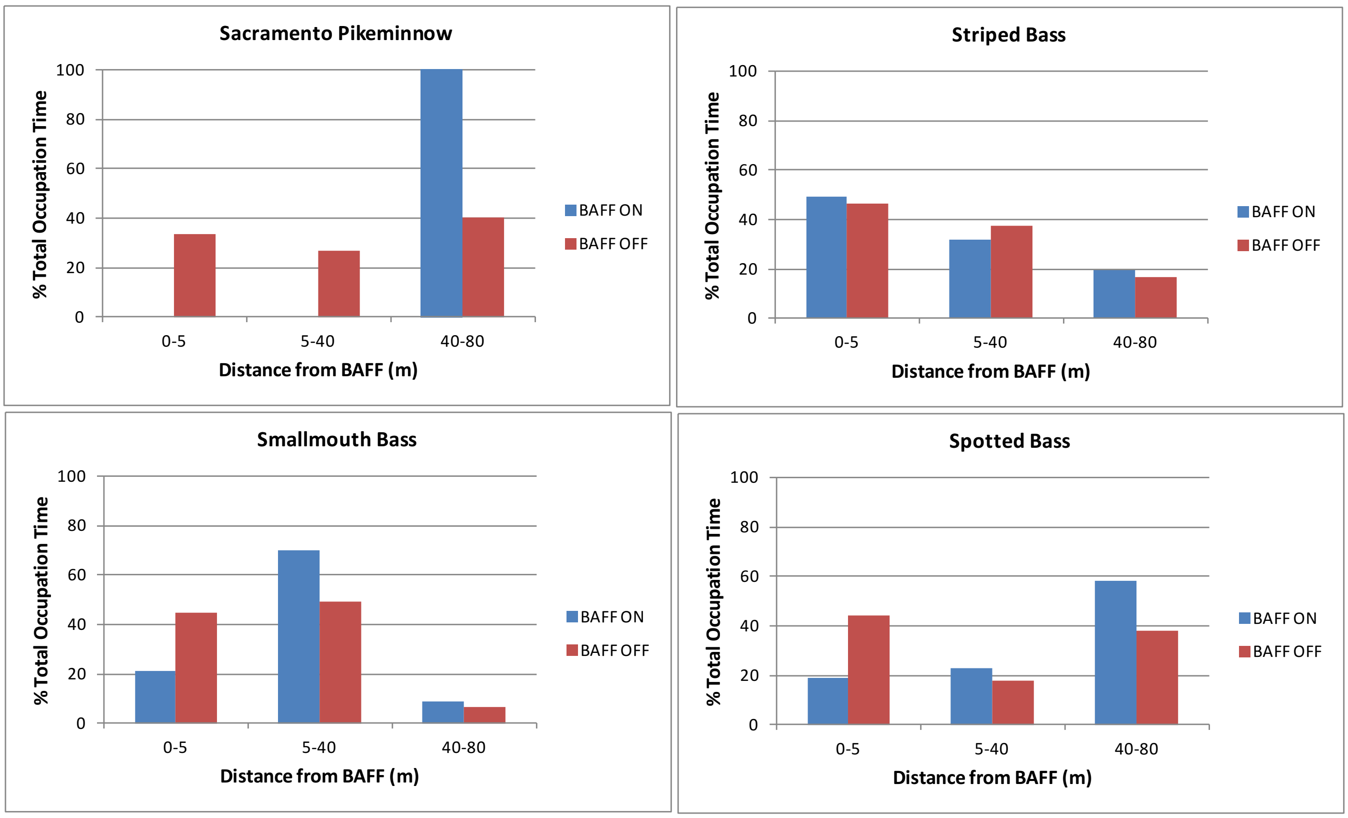
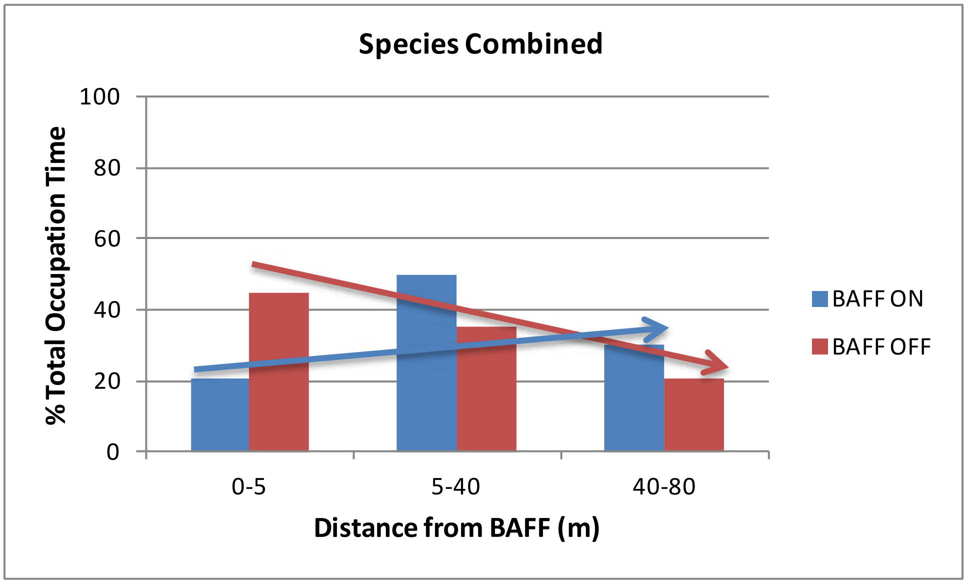


Figure 3.7-25 Percent of Total Occupation Time by Spatial Polygon for Each Species and for the BAFF On and BAFF Off Conditions

The objective of the BAFF On/Off spatial comparison was to evaluate differences in predatory fish densities between BAFF conditions in the area immediately surrounding the BAFF. Sacramento pikeminnow did not occupy the area 0-40 m from the BAFF during the BAFF On condition but spent 60 percent of their time in this zone during the BAFF Off condition. Striped bass behavior suggests a negative relationship between occupancy rate and distance from the BAFF during both BAFF conditions, and within spatial polygon occupancy rate differences were small. Smallmouth bass occupied the 0- to 5-m and the 5- to 40-m polygons extensively, and differences in occupancy rates between polygons during the BAFF Off condition were similar but much higher in the 5- to 40-m polygon during the BAFF On condition. Spotted bass occupancy patterns suggest a positive relationship with distance from the BAFF during the BAFF On condition, and the 0- to 5-m polygon was occupied most during the BAFF Off condition.

The within- and among-spatial polygon occupancy rates for both BAFF conditions suggest that the operational state of the BAFF's deterrence features may have affected predator densities in the area immediately surrounding the BAFF. Sacramento pikeminnow, smallmouth bass, and spotted bass displayed avoidance behavior, indicated by increased occupancy rate with increased distance from the BAFF, during the BAFF On condition. Striped bass displayed similar occupation rate patterns within and among spatial polygons and BAFF conditions which may suggest operational condition had no effect. Fish behavior in association with the BAFF operational state is evident when occupancy rates are pooled among species (**Figure 3.7-26**). The apparent positive relationship in occupancy rate with increased distance from the BAFF during the BAFF On condition and the apparent negative relationship in occupancy rate with increased distance from the BAFF during the BAFF Off condition suggest predatory fish as a group showed avoidance behavior in response to the BAFF's deterrence features.



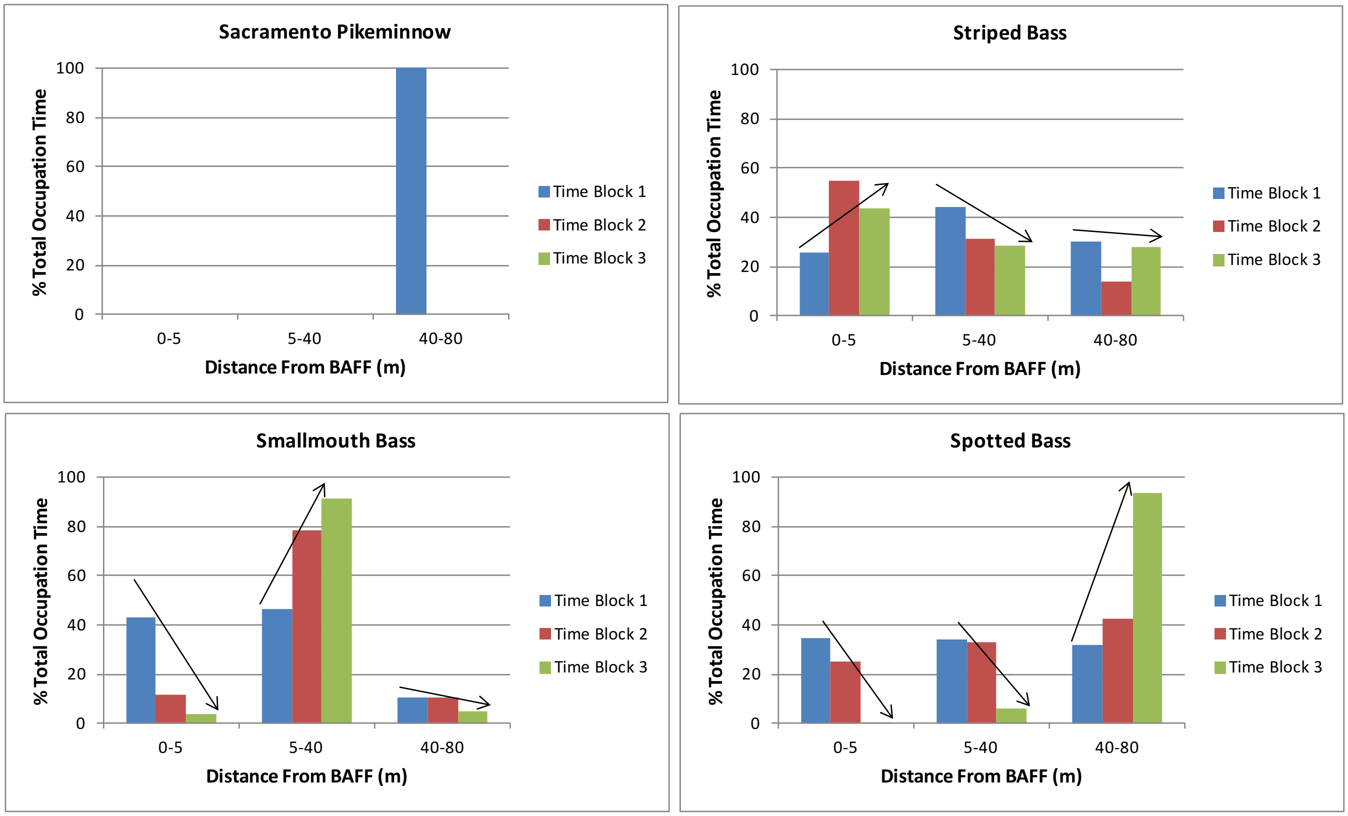
Note: Trends are shown by the arrows.

Figure 3.7-26 Percent of Total Occupation Time by Spatial Polygon for Species Combined and for the BAFF On and BAFF Off Conditions

Do Predatory Fish Become Conditioned to the BAFF through Time?

Percent of the total occupation time for each spatial polygon, each species, and each time block is shown in **Figure 3.7-27**. Striped bass occupied the 0- to 5-m spatial polygon most frequently. In this spatial polygon, occupancy rate was greatest during time block 2 (55 percent, time block 1 26 percent and time block 3 44 percent), and there appears to be a positive relationship between time and occupancy rate. There appears to be a negative relationship between time and occupancy rate in the 5- to 40-m polygon. The 40- to 80-m polygon was occupied least frequently, and there appears to be a negative relationship between time and occupancy rate.

Smallmouth bass occupied the 5- to 40-m spatial polygon most frequently during all time blocks. In this spatial polygon, occupancy rate was greatest during time block 3 (91 percent, time block 1 46 percent and time block 2 78 percent), and there appears to be a positive relationship between time and occupancy rate. There appears to be a negative relationship between occupancy rate and time in the 0- to 5-m polygon, and the difference in occupancy rate between time block 1 and time block 3 was large (34 percent). The 40- to 80-m polygon was occupied least frequently, and there appears to be a negative relationship between time and occupancy rate.

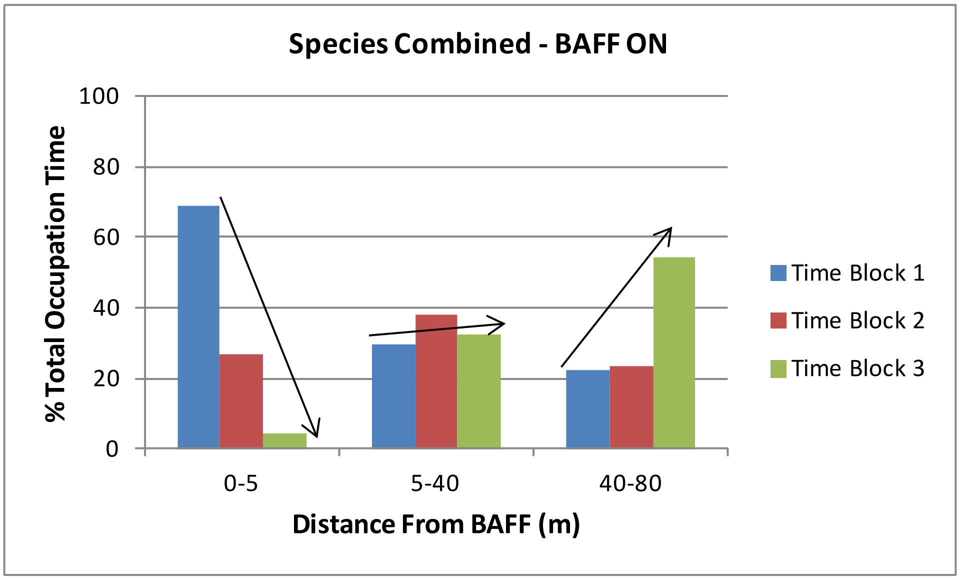


Note: Trends are shown by the arrows.

Figure 3.7-27 **Percent of Total Occupation Time by Spatial Polygon for Each Species, Each Time Block, and the BAFF On Condition**

Spotted bass occupied the 40- to 80-m spatial polygon most frequently. In this polygon, occupancy rate was greatest during time block 3 (94 percent time block 1, 32 percent and time block 2 42 percent), and there appears to be a positive relationship between time and occupancy rate. The 0- to 5-m polygon was occupied least frequently, appears to be a negative relationship between occupancy rate and time, and the difference in occupancy rate between time block 1 and time block 3 was large (40 percent). The occupancy pattern in the 5- to 40-m polygon suggests a negative relationship between time and occupancy rate, and the difference in occupancy rate between time block 1 and time block 3 was large (28 percent).

The objective of this comparison was to evaluate whether predatory fish became conditioned to the BAFF's deterrence features through time; therefore, only those dates and times when the BAFF's deterrence features were operational were included in this comparison. Conditioning would be indicated by increased occupancy rates through time in the spatial polygons closest to the BAFF (positive relationship) and a corresponding decrease in occupancy rates through time in the spatial polygons furthest from the BAFF. Temporal patterns in occupancy rates of striped bass and, to a lesser extent, smallmouth bass in proximity to the BAFF may suggest these two species showed conditioning to the BAFF's deterrence features. Occupancy rates for both species increased through time in areas closer to the BAFF. Temporal patterns in occupancy rates of spotted bass in proximity to the BAFF suggest the BAFF's deterrence features became more effective through time. Spotted bass occupancy rates in the two closest spatial polygons decreased through time, and occupancy rates increased sharply in the polygon furthest from the BAFF. This particular pattern is also evident when occupancy rates were pooled among species (**Figure 3.7-28**). The results from this comparison suggest that certain species might become conditioned to deterrence features through time. However, predatory fish as a group appear to show increased avoidance behavior to deterrence features through time.



Note: Trends are shown by the arrows.

Figure 3.7-28 Percent of Total Occupation Time by Spatial Polygon for Species Combined and for Each Time Block

Does the BAFF's Operation Result in Increased Predation Rates of Juvenile Salmonids?

The fates of 330 of the 1,424 juvenile Chinook salmon detected in the study area were classified as predation events (23 percent predation rate) at the Fish Fates Conference. Of the 330 fish, 250 were preyed on upstream of the BAFF (76 percent), and 80 were preyed on downstream of the BAFF (24 percent). The average FL of released Chinook salmon was 138 mm (range: 104 mm to 215 mm). The average FL of Chinook salmon consumed by predatory fish was 137 mm (range: 106 mm to 208 mm). The fates of 86 of the 264 steelhead detected in the study area were classified as predation events (33 percent predation rate). Sixty-six steelhead were preyed on upstream of the BAFF (77 percent), and 20 were preyed on downstream of the BAFF (23 percent). The average FL of released steelhead was 214 mm (range: 119 mm to 258 mm), and the average FL of steelhead consumed by predatory fish was 220 mm (range: 184 mm to 258 mm).

The barrier condition was confirmed to be either on or off during 116 of the 330 Chinook salmon predation events and 24 of the 42 steelhead predation events; results are listed in **Table 3.7-8**. Predation rates increase with increased distance from the BAFF across all comparisons. Predation of both Chinook salmon and steelhead occurred least frequently in the 0- to 5-m spatial polygon and most frequently in the greater-than-80-m spatial polygon regardless of BAFF condition. Differences in predation rate were very large between the 0- to 5-m polygon and the greater-than-80-m polygon for both BAFF conditions. Differences in predation rate were similar within BAFF conditions, including species combined, and across spatial scales.

Table 3.7-8
Predation Rates for Tagged Chinook Salmon, Steelhead, and Species Combined for the BAFF On and BAFF Off Condition and Each Spatial Polygon

		Distance from BAFF (m)						
		0–5		5–80		>80		
		Number Eaten	Percentage of Total	Number Eaten	Percentage of Total	Number Eaten	Percentage of Total	Total Eaten
Chinook salmon	*BAFF On*	5	12	7	17	30	71	42
	BAFF Off	6	8	24	32	44	59	74
	Total	11	9	31	27	74	64	116
Steelhead	*BAFF On*	0	0	4	17	20	83	24
	BAFF Off	1	6	3	17	14	78	18
	Total	1	2	7	17	34	81	42
Combined	*BAFF On*	5	7	11	17	50	76	66
	BAFF Off	7	8	27	29	58	63	92
	Total	12	8	38	24	108	68	158

The effective range of deterrence features extended approximately 80 m from the BAFF, and if these features affected predation rates by temporarily disorienting juvenile salmonids, a high percentage of predation rates would be expected to occur within 80 m of the BAFF compared to predation rates found greater than 80 m from the BAFF. In addition, if installation of the BAFF increased predator densities in the area immediately surrounding the BAFF and contributed to increased predation, high predation rates would be expected within 80 m of the BAFF and in particular in the 0- to 5-m polygon.

Predation rate spatial patterns across all comparisons suggest the BAFF's physical and deterrence features did not contribute to increased predation in the area immediately surrounding the BAFF. It is important to note that predation rates in the study area during the study time period in the absence of a BAFF's physical and deterrence features (i.e., true baseline predation rates) are unknown; therefore, results of the study should be interpreted carefully. Predation rates in the entire study area may have been influenced by the presence and operation of the BAFF.

3.7.4 ACTIVE HYDROACOUSTICS

METHODS

As described previously, tagged fish can be tracked and their movement patterns mapped in relation to the barrier and other features. While this type of analysis is extremely useful in describing fish movement patterns around the barrier, the results are limited by the number of fish that are tagged. For example, this type of analysis does not allow for an estimate of total potential predator density to be determined. Additionally, individual fish cannot be identified with this approach, and this approach assumes that "predator-sized fish" targets are predators.

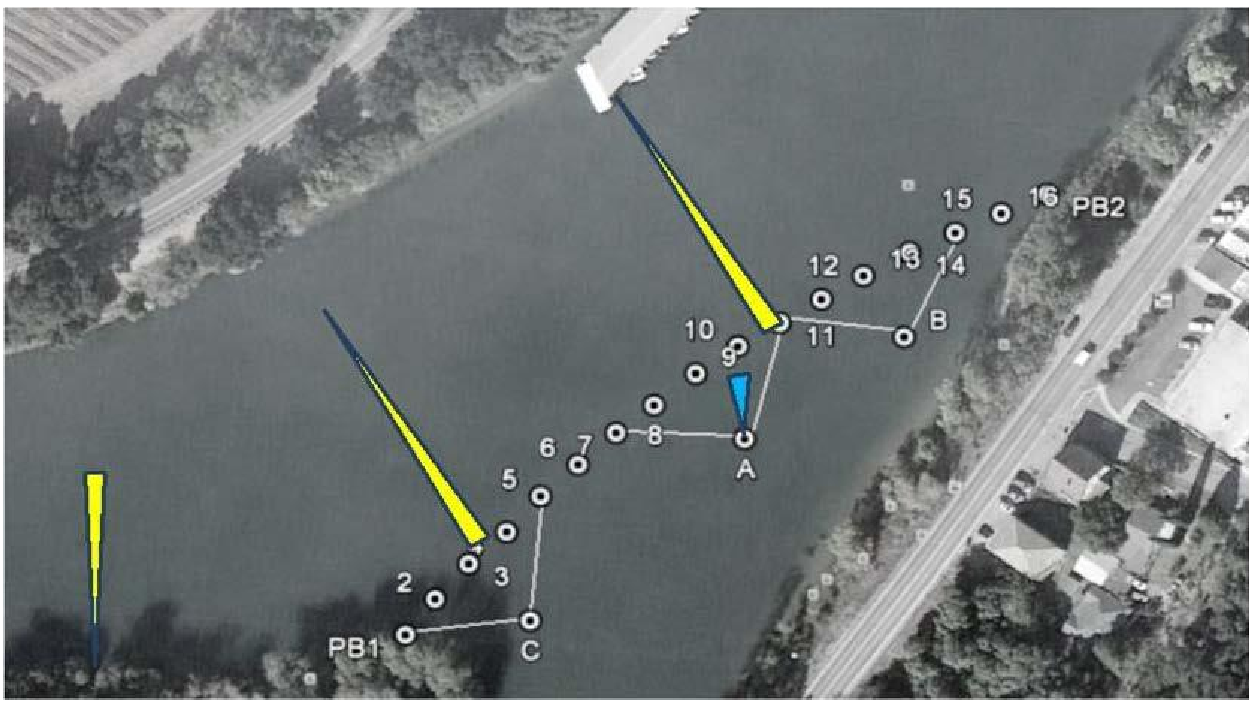
The active acoustic[5] component of the predator study was designed to gather data to determine how predator densities vary through time in the study area and to correlate densities and changes in distributions with barrier operations.

Depending on the species, a predator may, while passing by the barrier, prey on other fish if the opportunity presents itself, or it may stay closely associated with the structure. Predators may also move closer to or away from the barrier, depending on tidal, diel, operational patterns, or other parameters.

The density and spatial distribution of potential predator-sized fish targets were determined using active hydroacoustics. A series of BioSonics, Inc's® DT-X Digital Scientific Portable Echosounders (i.e., split-beam transducers) and a DIDSON (Sound Metrics Corporation) sonar unit were aligned to monitor the reach of the river near the BAFF (**Figure 3.7-29**).

Split-Beam Data Collection and Processing

All split-beam acoustic data were collected using the DT-X Digital Echosounder operating at either 200 or 420 khz, depending on the location. For the purposes of this report, data are reported from a single 420-khz transducer placed at Dagmar's Landing and aimed across the Sacramento River toward the BAFF (**Figure 3.7-29**). Software used in the analyses of data was SonarData's (Myriax Software Pty Ltd. since 2008) Echoview®, version 5.3.39. The locations of the transducers were geo-referenced, allowing placement of fish positions in the three-dimensional context of the river.



Source: Reclamation 2013

Note: Split-beam (yellow) and DIDSON (blue) acoustics used during the 2012 BAFF surveys.

Figure 3.7-29 **Overview Showing Approximate Locations, Aiming Angles and Areas of Coverage for Both Hydroacoustic Surveys**

---

[5] Active hydroacoustics is a means of measuring the range to an object and its relative size by producing a pulse of sound and measuring the time it takes for an echo to return from the object and the amplitude of the returned echo. The range is calculated as a function of the speed of sound and the time it takes for the echo to return.

The unit at Dagmar's Landing was suspended on a metal pipe hanger located at the end of the dock on the downstream side of the houseboat used for equipment storage (see **Figure 3.7-29**). The transducer was pointed into the river, parallel to the boat slips on Landing 63. The depth of the transducer was about 0.8 m below the surface with the transducer was aimed at a heading of 165 degrees and pitched down at 1.5 degrees. The maximum effective range was about 62 m, which was reduced to about 58 m when the BAFF was on. At this range, the transducer was able to detect fish across almost the entire depth of the water column in front of the BAFF.

All data were collected using BioSonics' Visual Acquisition™ Software, version 6. Data were recorded as a new file every 30 minutes to minimize chances of data loss during a system failure. Data collection thresholds were set at -75 db, 5 pings per second (pps), and a 0.4-millisecond (ms) pulse width. Data were downloaded at least once a week.

Because of the frequency at which it was operated and the amount of power used to generate the ping, operation of the DT-X hydroacoustic unit introduced a substantial amount of noise into the water column. This noise affected both the passive acoustic receivers used for detecting tagged fish and, to a lesser degree, the acoustic Doppler current profilers being used for flow measurement; the effects on the tag tracking equipment were most noticeable. The introduced noise did limit, to an extent, the ability to do real-time tracking of tagged fish. Noise had the primary effect of creating large file sizes for the tagged fish and slowing analyses. To limit the problems associated with equipment interference, the hours of active acoustic operation were limited to one hour every four hours, or approximately six hours of collection time per day. If it was known that a group of tagged fish would be arriving at a given time, active acoustics would be stopped to allow for real-time detection of the fish.

As a first step before analysis, files were visualized by "play-back" in Echoview, providing a high-resolution color echogram of the file. Comments were recorded on presence of fish targets, as well as on regions overshadowed by acoustic interference. The primary source of acoustic interference was volume reverberation from bubbles introduced by boat traffic or high wind events. It was during this phase that file sets were selected for exclusion from further analyses. Although fish targets can be seen in echograms that were ultimately excluded, the overshadowing noise prevents effective analysis of the traces. In a few rare cases, file sets were excluded because, for one reason or another, the sonar head was bumped and shifted out of position.

After the files were imported into Echoview, calibration consisted of entering data on water temperature (used for calculating the speed of sound) and acoustic system information, including beam angle, frequency, and range gates for analysis. Unlike with earlier versions of Echoview, all calibration information stored in the file is now imported directly to Echoview, negating the need for calibration variables other than water temperature to be input.

Two techniques were used to limit the effects of unwanted background noise or reverberation. On clear, calm days, most of the volume reverberation was observed at a relatively low level. Because data files were collected using a -75-dB threshold, and because this level is considerably lower than the acoustic size of the cutoff for predatory fish-sized targets (-40 db), the threshold eliminating data between the collection threshold and the lower cutoff for fish size of -40 db (16-centimeter-long fish) removed most data that would interfere with data analysis. However, on days with higher turbidity attributable to runoff-related increases in discharge, and when winds were present, a subtraction echogram was employed, along with thresholding (i.e., identifying target thresholds), to minimize the unwanted effects of background interference. Even with the increased threshold and background subtraction, some regions were masked by high noise events, and no fish data could be recovered from these regions. These files were removed and not included in the analysis.

Background noise subtraction was always done before any thresholding of the data during the analysis phase. The reason for this is that thresholding ignores targets smaller than a certain size. Background noise removal reduces the signal strength of the entire echogram, essentially subtracting the gain in signal strength upon a target imposed by other scatterers in the water column within that ping. Thus, background noise removal reduces target size to an extent. The effect, although small, can have an impact at the threshold level.

Echoview provides two options as virtual variables to remove background noise, and both were used. Both methods are used on the volume back scattering strength (SV) echogram (20LogR), which is later converted back to a target strength echogram (40LogR). The first option allows a background noise removal operator to be used to specify the maximum noise as measured at 1 m, as well as a minimum signal-to-noise ratio. The other option is to generate a noise echogram. This was done occasionally during the study because it appeared that beyond a certain point, Echoview's Background Noise Removal algorithm does not operate effectively, and more noise could be removed by generating an echogram. With either method, the background noise echogram is designed to mirror the noise signal being returned. In Echoview, this signal is then subtracted from the SV echogram. Visual observation was used to determine what appeared to be the most effective noise removal level. The next step was to convert the noise-subtracted echogram back to a target strength echogram from which a single targets (ST) echogram was created and on which all data used for analyses was exported.

The ST echogram essentially functions as a filter placed on the raw target strength echogram, removing unwanted signals. First, the signal was further thresholded to the -40-dB level, which is the minimum cutoff for predatory fish. Pulse width was used as a primary filter to test the returning wave shape. Echoes from reverberation should have corrupted wave shapes in comparison to point-source target echoes (fish). The pulse width was measured at the half amplitude (endpoint criteria = -6 dB). The pulse width measurement was compared with the nominal transmitted shape (0.4 ms). Echoes with pulse width measurements less than 0.3 times the nominal or greater than 1.5 times the nominal were rejected.

The next filter is the maximum allowable beam compensation. This filter puts a limit on how far off the center axis of the transducer beam a target can be. For these analyses, the level was set at 10 dB. A target could be 10 dB off peak and still be included in the analysis. The further off the center axis that a target is, the less reliable the estimates of size and position are.

The final filter involved examining the standard deviation of the angles of the samples in both the X and Y range. Samples that fall outside the above-specified ranges would be rejected. A line of maximum range was also included. This is a line beyond which echoes would not be analyzed. This range was set to exclude the first contact from the BAFF that the computer would interpret as a fish trace. The last stage of establishing this filter involved laying grid lines over the echogram. The range grid (5-m spacing) and time component (10 minutes) were what Echoview used to create cells of data during the export phase.

The last step in Echoview before data were exported for analysis was to generate fish tracks. The human eye can easily see what constitutes a candidate fish track and what does not, but the computer must be programmed to accomplish this task. This process is called trace formation. Trace formation may be either 2D, using range and time, or four-dimensional, using time and X/Y/Z position produced by a split-beam system.

Echoview's α−β Fish Tracker implements a fixed coefficient filtering method as presented by Blackman (1986). The filtering process selects out single targets as candidates for a track. The algorithm is applied to a single target detection data. The sensitivity of the tracker to unpredicted changes in the position and velocity of a fish is controlled by the alpha and beta gains, respectively. Each fish echo that has passed the echo extraction tests is characterized by a ping number (time) and range. These provide X and Y coordinates. When a candidate echo is received, it "opens" a new trace. The range of this first seed echo is projected horizontally. A "tracking window" is centered about this position to provide a range window in the following ping. Any echo inside this range window must by definition be correlated to the seed echo. If multiple echoes fall inside the window, a best fit is calculated, and that echo is linked to the original seed echo, providing a fish trace containing two echoes. Again, the echo that is closest to the center of the window is selected to be linked to the growing fish trace. A maximum range can be specified, outside of which echoes will not be included. This is useful when fish are close together to avoid the track jumping from fish to fish.

Fish tracks were used to provide single targets used in density calculations. Because of the number of tracks involved and the time necessary to review all the tracks, the movement of one fish could be shown as several tracks. Fish tracking parameters were adjusted to result in the greatest number of acceptable tracks without causing inclusion of traces formed by the track jumping from fish to fish. As a result, at high densities the number of fish is likely underestimated because single targets are excluded from tracks.

The analytical strategy for processing this data set was to minimize the type 2 errors. A type 1 error is defined as missing a valid fish, and a type 2 error is defined as including a false fish or one created from reverberation or interference. Given the noise levels observed during data collection, it was concluded that the type 2 errors could overwhelm the data set and provide a greater source of bias than could type 1 errors. Consequently, echo-selection criteria and trace-formation criteria were used to minimize the formation of false fish traces. The high noise levels combined with this strategy may have resulted in the loss of some smaller fish targets.

Exporting the trace formation process produces a data file with a line (record) for each fish trace. Traces are coded by date and time and contain information such as mean target strength, range, off-axis distance, velocity, direction of travel, and the number of single target pings included. Exporting data by grid cells provided a density spreadsheet for every 10-minute block of data, which gave the average density of fish per unit volume of water and standardized the effects of change beam volume with distance.

Data files produced by the trace formation process were imported into Microsoft® Excel spreadsheets. The range and angular position columns were selected in each file and plotted as a scatter plot. The scatter plot was then evaluated for data groupings to search for anomalous distributions of targets. At this phase, the largest issue was attempting to determine whether fish traces were indeed fish and not debris or apparent large fish created from multiple echoes of small fish close to each other, resulting in the acoustic signal of a large individual. Several methods were employed to look at overall data quality. First, fish tracks were classified as debris or fish. This step is best done visually in Echoview. Large fish typically exhibit certain behavior as they move through the transducer beam. For this reason, fish traces do not appear as a straight line but instead display movement right and left in the channel as the fish pass. Further, during high-flow events, most debris is present near the surface as it floats by. An X/Y plot of candidate fish traces often revealed the presence of debris. Some of the deeper traces were less clear, but typically subsurface debris target strengths are lower than the threshold used to delineate large fish. By restricting analyses to exclude certain portions of the water column, much of the debris was removed.

DIDSON Data Collection and Processing

DIDSON data were collected and analyzed using the same techniques used for other acoustic data with some minor differences related to the type of data collected. Unlike the split-beam transducers employed upstream of the BAFF, the DIDSON sonar is a multibeam unit employing up to 96 beams (when run in high-frequency mode) with an angle of 0.3 degree in the horizontal and 14 degrees in the vertical, producing a 29-degree by 14-degree beam. Although the DIDSON sonar does have a vertical component to the beam, the data obtained with the vertical component are not available for multibeam analysis. For this reason, all data output is 2D (range and left-right positioning in the beam).

The DIDSON unit was set to collect data hourly, beginning on March 6, 2012, and stopping on April 30, 2012, when disassembly of the BAFF began. It was operated in high-resolution mode during the entire study period, and the maximum distance sampled was 10 m from the face of the unit.

Acoustic processing of DIDSON data includes the following series of steps, resulting in a final output:

1. Examine the raw data;
2. Remove excess noise and background data;
3. Conduct smoothing and beam dilation;
4. Improve multibeam Target Detection;
5. Filter targets;
6. Convert targets;
7. Detect fish tracks; and
8. Create spreadsheet summaries of tracks.

Examining the raw data allowed the team to determine where potential processing problems might arise and which techniques might prove most useful for analysis. Files had to be deleted from analysis when partial shading of the image occurred as a result of movement of debris or incorrect aiming of the DIDSON sonar and when excessive background interference limited the utility of the data.

Removing excess noise for the most part is the same as removing the background interference. It refers to removing a portion of the DIDSON image that was not relevant to the analysis, typically the bottom or structure images. Several options existed for background noise removal, both in the DIDSON software and in Echoview. In either case, the end result was to produce a dataset that retains only the portion of the image in which fish were present. Files were preprocessed using a variety of techniques to determine the most effective means of removing background data. In Echoview, a ping subset was created whereby a series of background snapshots were taken that could then be used as a reference point. Using a sample statistic operator, the team then subtracted this subset from all echogram frames, which in theory leaves only the moving traces of the fish behind. This method is sensitive, however, to the frames used as a basis for removal, and any minor movement results in the generation of false targets. For example, sand waves on the river bottom, while appearing static, caused issues for fixed background subtraction in Echoview. Over time, shifting sand waves would result in multiple target detections, and the movement of sand to a new position caused this section of the background to not be removed.

The other option for background noise removal was available in both Echoview and the DIDSON software. This technique does not assume a static background and allows for some slow movement of the background. In both cases, the software takes a mean image of a previous number of specified pings that are subtracted from the current ping. Thus, slow-moving objects (e.g., sand waves) would not be detected as motion because the previous pings were only fractions of a second apart. Although this technique is effective in Echoview, the team found processing time to be slow because of the large file sizes. It was more efficient to allow the DIDSON Control and Display software to perform background subtraction and data reduction and create its own Convolved Samples Over Threshold (CSOT) files, which could then be imported to Echoview for analysis. The DIDSON CSOT files were created in batch mode, and after a file directory was specified, the data reduction could proceed autonomously. During this phase, not only was the background removed, but frames empty of detected movement were deleted, which, when few fish were present, could reduce file size by more than 90 percent, greatly speeding up further analyses. To determine the best settings for noise removal file, sample files were selected and run through the process and examined to ensure that fish targets were not being dropped unnecessarily. This was accomplished by adjusting the cluster area size and the threshold above the background under the record options tab of the Image Capture dialog menu in the DIDSON software.

After the background was removed from the multibeam echogram, a few steps were employed to improve target detection. Data threshold settings allowed the team to ensure that the proper targets were included for analyses. Two additional data operators in Echoview were used to further increase the visibility of targets. The first step was to use a median operator, which helps smooth the image without imparting any serious changes to future analyses. Adjusting this smoothing variable allowed for greater or less target definition. For smaller fish in particular, the team had trouble getting the target recognition to operate properly, so a dilation filter was applied to the smoothed image. This made targets easier to select but artificially increased the target size by one beam width on either side of the target. The effects of this increase in size were subtracted manually from the Microsoft Excel spreadsheets of fish length data.

The next phase was to detect multibeam targets and to filter targets according to length criteria. Again, a series of target criteria were tried until it visually appeared that the software was correctly identifying most fish targets. With larger fish, this was never an issue; changes in parameters primarily affected only small targets. To filter targets, the minimum acceptable fish length was identified, and all targets below that threshold were excluded.

To allow Echoview to identify fish traces and to provide data suitable for analyses, multibeam data were then converted to a single-target echogram, and at this point, further analyses are identical to those used for the split-beam data. The only difference was that instead of target strength being employed to describe fish size, the team had an actual length of the fish as detected by the multibeam target selection criteria substituted in place of target strength.

Selecting and creating fish tracks at this point involves using the same algorithms and selection parameters described previously. The only difference when fish tracking with DIDSON data is the loss of the minor axis component (used to calculate depth of fish in the water column). Because multiple beams are used to reference the target, the result is usually accurate positioning—much more so than with split-beam data, which can have a relatively high degree of position inaccuracy under some conditions. With better positioning data, fish tracks are also likely to be better defined because the position accuracy allows the tracking algorithm to perform better. For the DIDSON sonar data, the down- and 32 cross-field resolutions are restricted to 512 by 96 pixels; thus, targets at closer ranges are better resolved because of pixel size. Measurement accuracy decreases at further ranges because the beam widens with distance. Further, if the DIDSON sonar is operated in low-frequency mode, this error is compounded because the beams are wider. Another potential source of measurement error is a target's aspect angle relative to the beam. In prior studies using a side-aspect deployment, fish aspects close to 0 (perpendicular to the beam) yield the most accurate lengths (Burwen et al. 2007).

DIDSON fish tracks were exported as time-stamped variables for further analyses. Because the DIDSON data are two-dimensional, there is slightly less basic information available for positioning fish in the water column. In addition to the direction of travel and the length of the fish, several other export variables, including target thickness and target range extent, potentially provide useful information for species delineation.

Statistical Analyses and Data Presentation

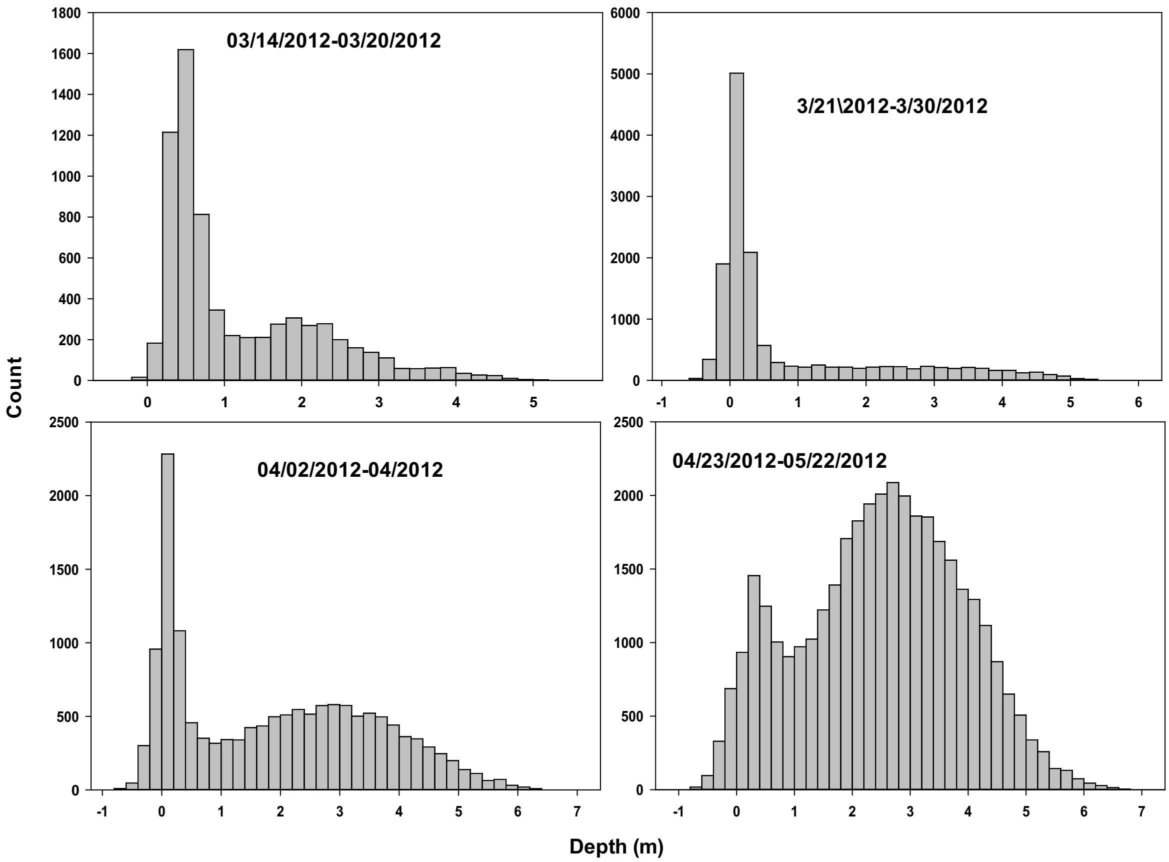
Data were analyzed using several different methods, depending on the hypothesis being tested. All graphical data were presented using SigmaPlot™ version 12 (Systat Software, Inc.), and statistics were presented using SAS® version 9 (SAS Institute, Inc.). Trends for which statistics were deemed not appropriate were depicted graphically. If the basic statistical assumption of normality was violated in all cases, an appropriate test was employed, depending on the comparison.

When a lateral position of a fish in the water column was being examined, data had to be standardized to account for change in sample volume with distance from the transducer. The transducer beam was divided into 5-m horizontal bins. The volume of each conic section was then calculated. Fish counts for each bin were then divided by the bin beam-volume to determine a relative fish density. These densities were then standardized whereby the sum of the bin densities was 100. This allowed comparisons using a chi-square test.

Results and Discussion

Overall, both the DT-X split-beam system and the DIDSON sonar appeared to perform well over the course of the study. Each system had its own limitations. Overall almost 72,000 candidate fish traces were generated with the DT-X transducer, and approximately 37,000 traces were generated with the DIDSON sonar.

The primary limitations experienced with the DT-X transducer related to an inability to analyze data obtained on windy or very rainy days and times when boat traffic was persistent. High winds and rain result in considerable surface disruption and introduce small bubbles into the water column, which can effectively blind the transducer. The transducer was located just below the surface and scanned sideways into the channel, which made it particularly susceptible to these effects at longer ranges. When the BAFF was being installed, the continuous presence of the barge and work boats prevented any long-range work, so no long-range data are presented here. Because high amounts of surface debris were associated with runoff at certain times, particularly during the middle of March, all targets closer to the surface than 0.5 m were removed from the analysis dataset (**Figure 3.7-30**). This decision resulted in the loss of near-surface fish traces, but available graphs of the data and review of the traces suggest that the impact was minimal at best. Overall, about 25 percent of the eligible traces were deleted by removing the shallower targets, reducing the total number of traces to be used for analyses from about 72,000 to about 52,000. A summary of the remaining data still shows the potential impact of surface debris, but the total is less than 10 percent of all data.



Source: Reclamation 2013

Note: Predominance of shallow traces shows the contributions of debris to overall number of traces detected.

Figure 3.7-30 Depth Distribution of Traces Detected

If surface debris detected by the monitoring equipment were truly surface debris, it would be expected that removing shallow targets would have removed these traces. Unfortunately, two issues are associated with this approach, and neither can be easily solved. Although the team attempted to mount the transducer as rigidly as possible, the fact that it was attached to a floating dock meant that the transducer would move, and when translated out over 50-60 m, a change in the pitch of the transducer of only one-tenth to two-tenths of a degree would result in a change in perceived target depth of 20 centimeters or more. Thus, a surface target can appear deeper or shallower in the water column than it really is. Second, split-beam data are not always as accurate as they could be. **Figure 3.7-11** illustrates the variability in calculated position along the major and minor axes for a given fish track. The variation is almost 1 vertical meter between pings. Each ping is less than 0.2 second apart, so the error in measurement is only minimally contributed to by any changes in fish position. Finally, thresholding did help remove some of the surface chatter, but highly buoyant surface debris can send back much larger than expected target strengths because of the amount of air entrained in the debris.

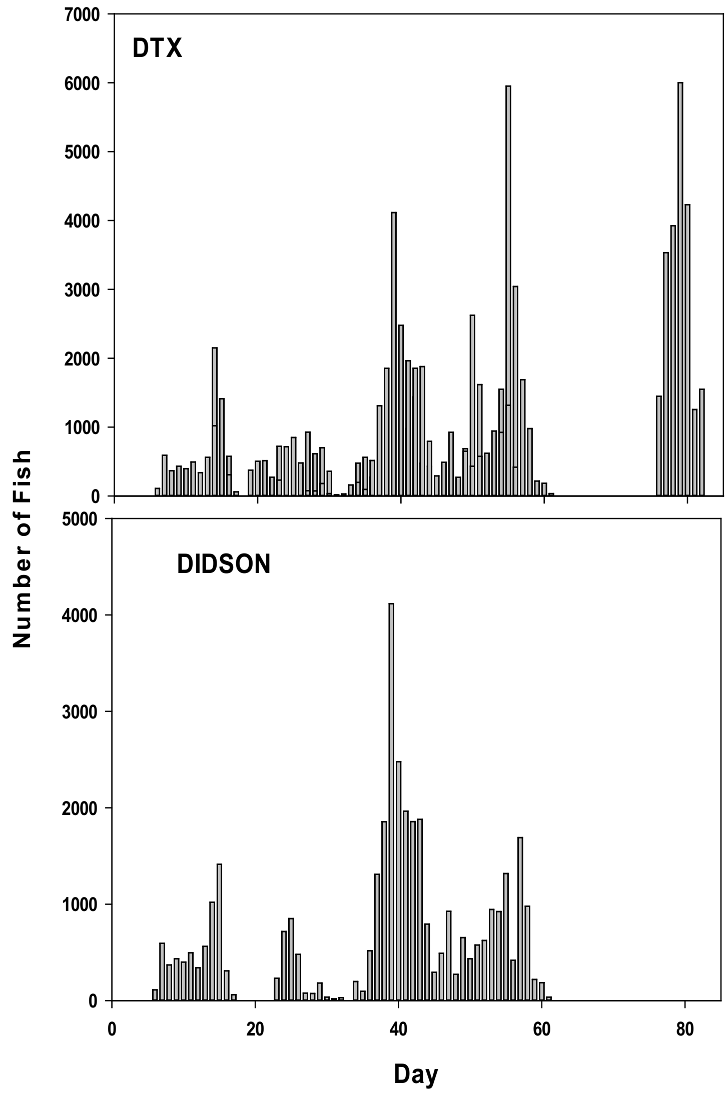
DIDSON data obtained in Georgiana Slough were not noticeably affected by the presence of debris. The team would not have been able to separate the data in the manner it did with the DT-X system if the data had been affected. There was no vertical component to the DIDSON data, so all data appear vertically in one plane. The multibeam nature of the data meant that turbulence and bubbles were a problem during analysis only in extreme cases. The target selection criteria used data generated from multiple beams to select valid targets. Small patches of turbulent sediment plumes and debris such as leaf litter did not meet the selection criteria either during multibeam target selection or following the length filter and are thus were excluded. Most debris observed was floating at or near the surface, and the deep placement of the DIDSON, along with a relatively short range of observation, minimized the impacts of debris; however, it also narrowed the zone of observation for fish traces.

Because hydroacoustics cannot differentiate between species of the same size, the ability to separate predatory from non-predatory fish introduces an unknown amount of error. Generally, by thresholding fish size, the team can discount many smaller forms, such as threadfin shad (*Dorosoma petenense*), which can be present in high numbers. Trap-netting completed by the USFWS and associated with earlier DCC studies suggests that most of the larger fish caught represented predatory species. Common carp (*Cyprinus carpio*) is essentially the only large non-predatory species continuously present in the study area; however, it tends to be found more commonly in backwaters and near the shore and was not a concern. Later in the season, as runs of adult American shad (*Alosa sapidissima*) began, the team's confidence in acoustic target delineation was reduced because the fish was present in the study area. Recently, researchers have shown success in delineating species of salmon based on characteristics of the multibeam data returned by the DIDSON sonar. The team will explore this possibility in the near future to determine whether similar determinations can be made for fish in the Delta.

Overall trends in fish numbers, disregarding any effects of the BAFF, were similar for the DIDSON and the DT-X systems (**Figures 3.7-31** and **3.7-32**). On numerous days, no data were obtained by one or both pieces of equipment; zero values are shown for those days. From the data, it is apparent that four distinct pulses of large fish moved through the study area during the operational timeframe of the BAFF. These data need to be correlated to tagged fish survival to determine whether there were differences in survival during and between those periods.

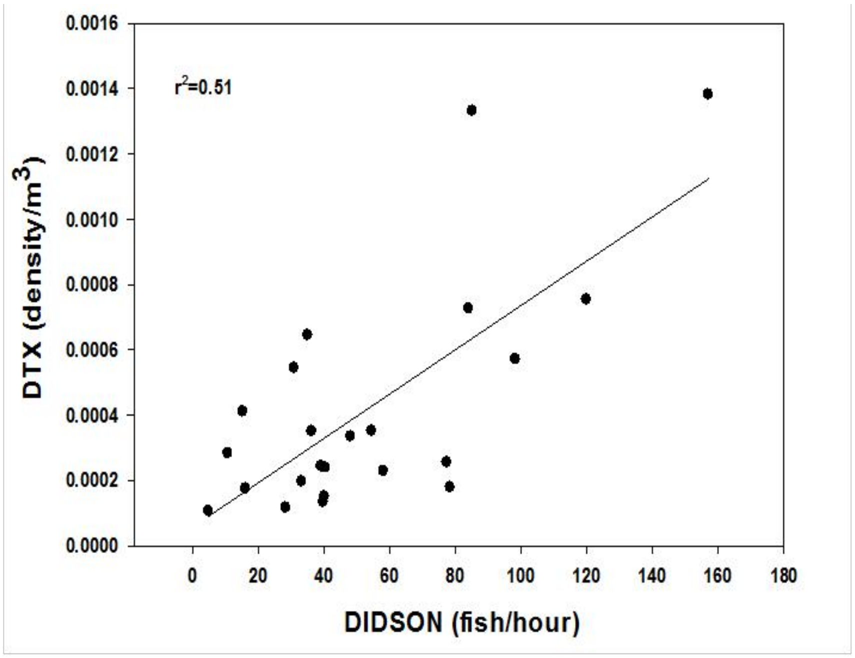
Of fish tracks observed near the BAFF during the operational period through the end of April, most moved in an upstream direction (**Figure 3.7-33**). In May, the net movement was still upstream, but directional travel was not as pronounced. Most of these earlier pulses of upstream-moving fish were more than likely primarily striped bass on their spawning run up the Sacramento River. Later in May, the team probably saw a combination of American shad and striped bass, but without concurrent netting, the team cannot say with certainty that this was the case.

The BAFF operation appeared to have no impact on the average position of larger fish in the water column (**Figure 3.7-34**). Although the sums of the hourly counts appeared to show a slight skewness toward the BAFF when it was in operation, a Kruskal-Wallis rank test on the average ranges by operational period indicated that the shift in distribution was not significant (p=0.249).



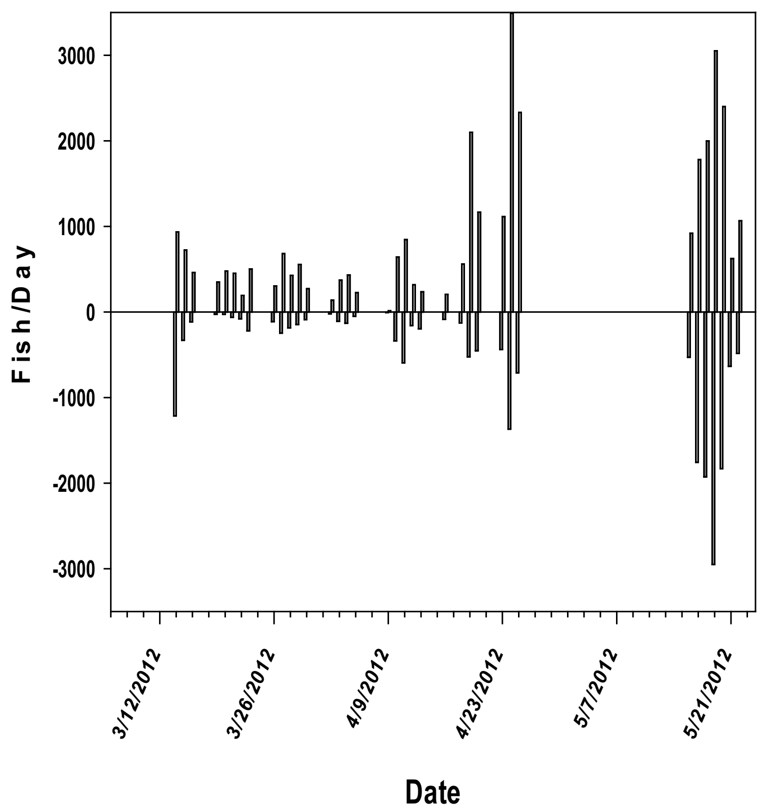
Source: Reclamation 2013

Figure 3.7-31 **Comparison of Trends Fish Numbers Observed Passing by the BAFF for both the DIDSON and DT-X Acoustic Systems**



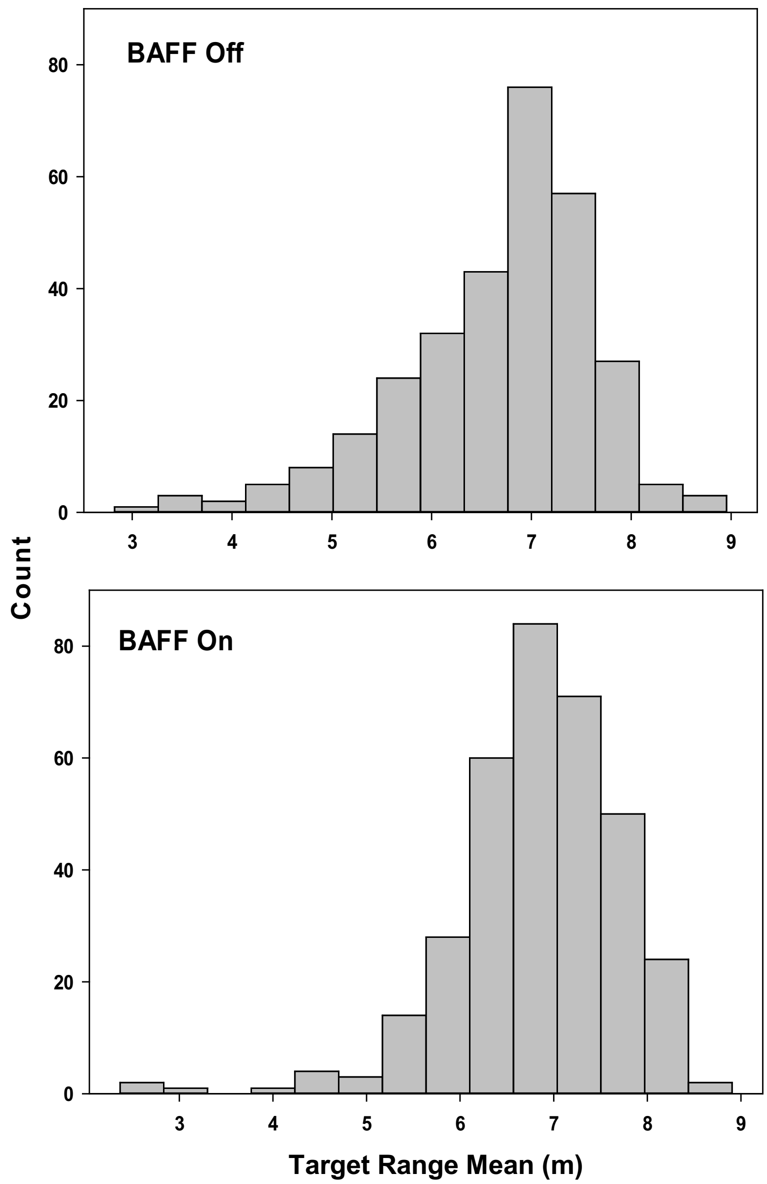
Source: Reclamation 2013

Figure 3.7-32 **Overall Correlation Between DT-X Fish Count Data and DIDSON Fish Count Data for 2012 at the Georgiana Slough BAFF**



Source: Reclamation 2013

Figure 3.7-33 **Daily Summary of Total Numbers of Fish Moving Upstream or Downstream Past the BAFF**



Source: Reclamation 2013

Note: For these graphs the first contact with the BAFF itself would be located at a distance of about 10.5 m. Data are counts of hourly average range.

Figure 3.7-34 **Average Range of Fish from DIDSON Transducer Face During BAFF Operations at Georgiana Slough**

3.8 2011 DELTA-WIDE SURVIVAL

This section revisits the 2011 BAFF study data to estimate survival of late fall-Chinook salmon to the terminus of the Delta at Chipps Island. In the 2011 BAFF report (DWR 2012), survival was estimated from the release site to telemetry arrays located 2 km downstream of the Georgiana Slough and Sacramento River junction. However, tags were also detected by telemetry arrays installed at Chipps Island to monitor fish tagged as part of the Vernalis Adaptive Management Program (VAMP) study (SJRGA 2013). Although estimation of survival to Chipps Island was not an explicit goal of the 2011 BAFF study, the additional data collected at Chipps Island from fish tagged as part of the 2011 study made such an estimate possible.

The goals of this analysis were to estimate reach-specific and total survival probabilities to Chipps Island and evaluate the potential for tag failure from battery life and consequent bias in survival probabilities. Because transmitters in the 2011 BAFF study were not designed to estimate survival to Chipps Island (i.e., designed to have long tag battery life), the study team expected to observe some tag failure before fish passed Chipps Island. Tag failure will negatively bias estimates of survival. Therefore, the survival estimates presented here should be interpreted cautiously because these estimates represent the probability of both the fish and tag batteries surviving to Chipps Island.

River discharge was high during 2011 BAFF study, and fish were likely to travel rapidly through the Delta. Therefore, bias induced by tag failure might be less than expected under lower river discharge. Given this rationale, the study team estimated survival to Chipps Island and evaluated tag travel times relative to expected battery life of the transmitters.

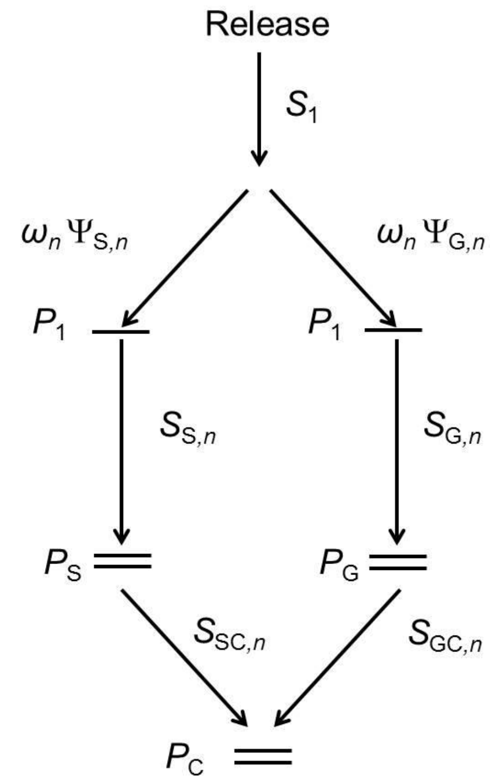
3.8.1 METHODS

The study team modified the mark-recapture model for the 2011 BAFF study to accommodate the Chipps Island telemetry station. This modification resulted in a mark-recapture model with telemetry stations at four locations: 1) the junction of the Sacramento River and Georgiana Slough (study array); 2) downstream of the BAFF in the Sacramento River (peripheral hydrophone site); 3) downstream of the BAFF in Georgiana Slough (peripheral hydrophone site); and 4) Chipps Island (**Figure 3.8-1**). The model, which was constructed using the methods of Perry et al. (2010), estimated three sets of parameters: survival (S_{hi}), detection (P_i), and route entrainment probabilities (i.e., probability of a fish entering Sacramento River or Georgiana Slough conditional on BAFF status) (Ψ_h) (**Table 3.8-1**).

Table 3.8-1
Parameter Definitions for the Mark-Recapture Model

Parameter	Definition
S_1	Probability of survival from release to array
$S_{S,n}$	Probability of survival from array to Sacramento River peripheral hydrophones
$S_{G,n}$	Probability of survival from array to Georgiana Slough peripheral hydrophones
$S_{SC,n}$	Probability of survival from Sacramento River peripheral hydrophones to Chipps Island
$S_{GC,n}$	Probability of survival from Georgiana Slough peripheral hydrophones to Chipps Island
P_S	Overall detection probability of the peripheral hydrophones in the Sacramento River
P_G	Overall detection probability of the peripheral hydrophones in Georgiana Slough
P_C	Overall detection probability of the peripheral hydrophones in the Sacramento River at Chipps Island
ω_{on}	Probability of arriving at the array with the BAFF on
$\Psi_{S,n}$	Probability of entering the Sacramento River conditional on BAFF status
$\Psi_{G,n}$	Probability of entering Georgiana Slough conditional on BAFF status

Note: The subscript "n" denotes parameters estimated separately for BAFF On and BAFF Off.



Note: A horizontal bars represents a telemetry location, and two horizontal bars represent the peripheral hydrophones.

Figure 3.8-1 Mark-Recapture Model Schematic Used to Estimate Survival, Detection, and Route Entrainment Probabilities

Survival probabilities estimate the probability of surviving from location *i* to location *i*+1 within each route (*h*). Detection probabilities estimate the probability of a tag being detected at a given location, conditional on the fish surviving with an operational transmitter. Route entrainment probabilities estimate the probability of a fish entering route *h*—in this case, the probability of entering the Sacramento River (route "S") or Georgiana Slough (route "G"). In addition, survival and route entrainment probabilities were estimated for BAFF On and BAFF Off treatments. This required inclusion of an additional parameter in the model, ω_n, which estimated the probability that fish would arrive at the river junction during BAFF On (ω_{on}) and BAFF Off (ω_{off}) treatment periods.

The data for the model are composed of observed counts of detection histories that define whether fish were detected at each telemetry station, the route of detection, and the BAFF treatment at the time fish were detected near the BAFF (**Table 3.8-2**). Each detection history is composed of four detection codes. The first code simply indicates that fish were released upstream of the BAFF and is coded with a "1" for all fish. The second code indicates fish not detected in the array ("0"), fish that entered either the Sacramento River ("S") or Georgiana Slough ("G"), and the BAFF operation when fish were detected ("on," "off"). Fish were assigned a route based on observing the final disposition of 2D tracks as determined at the Fish Fates Conference. The third code indicates whether fish were detected at peripheral hydrophones downstream of the BAFF in the Sacramento River ("S"), Georgiana Slough ("G"), or at neither site ("0"). The fourth code indicates whether the fish was detected at Chipps Island ("C"). For example, a fish that arrived in the array when the BAFF was on, exited the array via the Sacramento River, was detected at downstream peripheral hydrophone exit site, and was detected at Chipps Island was coded as "1 Son S C." A fish that entered the array when the BAFF was off and entered Georgiana Slough but was not detected at the downstream peripheral hydrophone, but was detected at Chipps was coded as "1 Goff 0 C" (**Table 3.8-2**).

Table 3.8-2
Detection History Frequencies Used in the Mark-Recapture Model to Estimate Survival, Detection, and Route-Entrainment Probabilities for Late Fall–Run Chinook Salmon Released in Spring 2011

Model	Detection History Overall	Frequency
Overall model	*1 Son Son C*	390
	1 Son Son 0	230
	1 Son 0 C	0
	1 Son 0 0	16
	1 Soff Soff C	359
	1 Soff Soff 0	210
	1 Soff 0 0	12
	1 Gon Gon C	7
	1 Gon Gon 0	42
	1 Gon 0 C	0
	1 Gon 0 0	2
	1 Goff Goff C	28
	1 Goff Goff 0	125
	1 Goff 0 C	0
	1 Goff 0 0	12
	1 0 Soff C	1
	1 0 Soff 0	1
	1 0 Gon C	0
	1 0 Gon 0	0
	1 0 Goff C	0
	1 0 Goff 0	0
	1 0 0 C	0
	1 0 0 0	65
Sacramento double-array model	*S1 0*	1
	0 S2	98
	S1 S2	1092
Georgiana Slough double-array model	*G1 0*	0
	0 G2	1
	G1 G2	201
Chipps Island double-array model	*C1 0*	208
	0 C2	75
	C1 C2	502

Fish classified as having been eaten in the array needed to be assigned to one of the three reaches (i.e., either the release site to the array, or from the array to each of the downstream detection sites). Therefore, fish classified as having been eaten upstream of the BAFF were assigned to the upstream reach by coding them as "1 0 0 0." Fish classified as having been predated downstream of the BAFF were coded either as "1 Son 0 0," "1 Soff 0 0," "1 Gon 0 0," or "1 Goff 0 0," depending on migration route and BAFF operation. Thus, fish eaten upstream of the BAFF are incorporated into the estimate of S1, whereas fish eaten downstream of the BAFF are incorporated into the estimates of either S_S or S_G.

Detection probabilities at the downstream detection sites (P_S, P_G, and P_C) were estimated by using detection data provided by two peripheral hydrophones that were implemented at each monitoring location. A mark-recapture model for peripheral hydrophones, described as double arrays by Skalski et al. (2002), allowed the study team to estimate detection probability for each detection location separately, and the overall detection probability of both peripheral hydrophone locations. Detection histories for the peripheral hydrophone locations are comprised of two codes indicating whether fish were detected by only one detection location, only the other detection location, or both detection locations (e.g., "G1 0," "0 G2," or "G1 G2").

Model parameters were estimated via maximum likelihood using optimization routines in the software Program USER (User-Specified Estimation Routine) (Lady et al. 2008). The standard error and profile likelihood 95 percent CIs were estimated for each parameter. Detection probabilities at telemetry stations where all fish were detected were not estimable and assigned a value of 1.

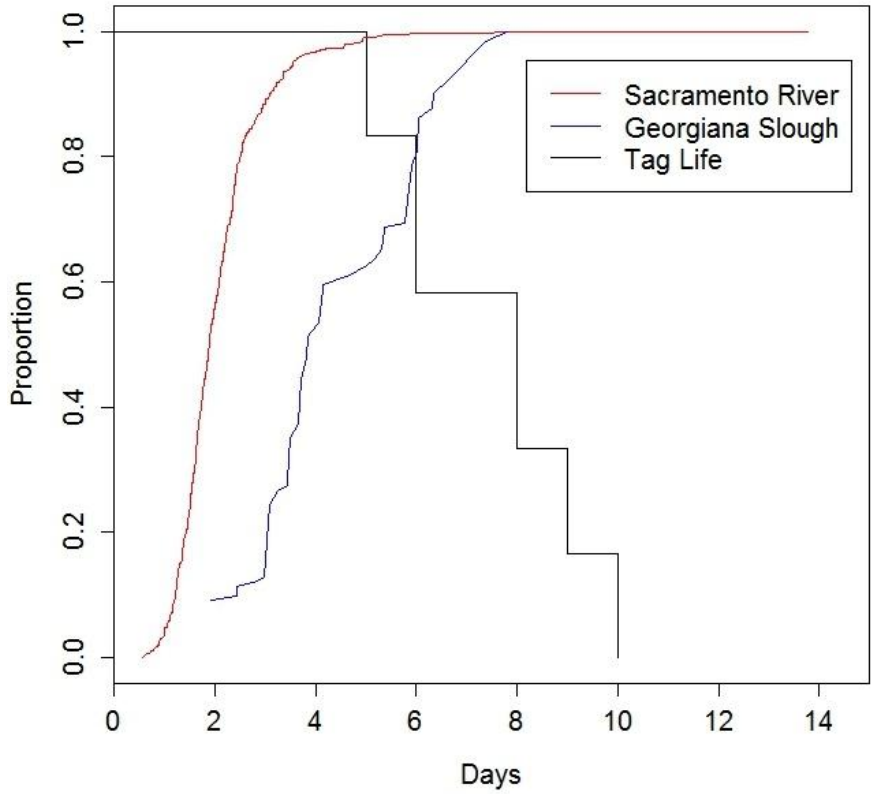
Detection data for the Chipps Island site were filtered to remove potential false positives in the dataset. Detection events that occurred before the release of the tag were removed. Emigration rate was also examined to remove false positives. Detection events with associated arrival times that required the fish to migrate at a rate of greater than 1m/s from the time of release were removed from the dataset. Finally, detections that occurred longer than 15 days after release were removed from the data because of tag life estimates.

A Kaplan-Meier tag life curve was fitted to tag life data provided by HTI using R statistical package (R Development Core Team 2011). HTI routinely reserves tags from each lot of production type for quality control purposes. In this case, 12 tags were reserved for quality control and were used to determine tag battery life. In addition, cumulative travel time distributions for each route (Sacramento or Georgiana Slough) were then plotted against the tag life curve. This allowed the study team to assess whether tagged fish arrived at Chipps Island before tags began failing.

Two alterations were made to classifications from the Fish Fates Conference. First, fish that were classified as "Predation Unknown" at the conference were assumed to have been live tagged salmonids, and their classification was changed to "Not Eaten." Second, the BAFF operation status of "Potentially Impaired" was changed to "On."

3.8.2 RESULTS AND DISCUSSION

Average tag life was 7.5 days (sd = 1.83) (**Figure 3.8-2**) and ranged from 5 to 10 days. Travel times to Chipps Island for fish migrating through the Sacramento River ranged from 13 hours to 13.78 days, and travel times for fish migrating through Georgiana Slough ranged from 1.9 to 7.81 days. Thus, for both routes, tags began expiring before fish arrival at Chipps Island by some fish, suggesting survival estimates are likely to be negatively biased to some extent.



Note: The black line represents tag life survival function. The red and blue lines represent the cumulative distribution of arrival time to Chipps Island by fish migrating through the Sacramento River and Georgiana Slough, respectively.

Figure 3.8-2 Tag Life and Travel Times for Fish Used in the 2011 BAFF Entrainment Study

Detection probability was much lower at the Chipps Island array than at other sites in the study area (P_C = 0.847) (**Table 3.8-3**). Detection probabilities at all other sites were greater than 0.91. The VAMP survival study for 2011 estimated an overall detection probability of 0.99 for this site for juvenile Chinook salmon, but the detection probability for the first release in this study was 0.75, approximately 10 percentage points lower than the study team's estimate (SJRGA 2013).

Survival for tagged fish traveling from the study area to Chipps Island was not significantly different between the BAFF ON and BAFF Off treatments for either route (Sacramento: X^2= 0.003, P = 0.959; Georgiana Slough: X^2= 0.4322, P = 0.511). In contrast, estimated survival for fish migrating through the Sacramento River was an order of magnitude greater than for fish migrating through the interior Delta using Georgiana Slough (**Table 3.8-4**). However, the travel times for fish using Georgiana Slough were considerably longer than for fish migrating via the Sacramento River. Consequently, survival estimates for fish entering Georgiana Slough are likely more negatively biased because of tag life than survival estimates for fish remaining in the Sacramento River.

Table 3.8-3
Estimates of Detection Probabilities and Standard Errors for All Telemetry Stations for Acoustically Monitored Late Fall–Run Chinook Salmon Released in Spring 2011

Station	Detection Probability	Standard Error
P_I	0.999	0.001
P_S	0.999	<0.001
P_{S1}	0.918	0.008
P_{S2}	0.999	<0.001
P_G	1	0
P_{G1}	1	0
P_{G2}	0.995	0.005
P_C	0.962	0.005
P_{C1}	0.870	0.014
P_{C2}	0.707	0.017

Note: PS and PG are the overall detection probabilities calculated from estimates of each detection location detection probability (PS1, PS2 and PG1, PG2, respectively).

The study team was able to estimate survival from the BAFF to Chipps Island using tags designed for the evaluation of the BAFF in 2011. This investigation was pursued primarily because high flows in 2011 reduced travel times through the Delta, which minimized bias related to tag failure. However, even with relatively quick travel times, the travel times for a portion of fish moving through both migration routes exceeded estimated tag life. Therefore, the survival estimates provided are likely to be negatively biased. Despite this bias, the survival estimates for fish migrating through the Sacramento River (0.610 and 0.614) are higher than estimates from Perry et al. (2010) (0.443 to 0.564) and Perry et al. (2012) (0.485 to 0.584). Conversely, the study team's estimates for fish migrating through Georgiana Slough (0.137 and 0.169) are lower than estimates by Perry et al. (2010) (0.332 to 0.344) and Perry et al. (2012) (0.179 to 0.314). The survival estimates for the interior Delta are prone to greater negative bias because travel through the interior Delta takes longer than travel using the Sacramento River. Thus, it is plausible that more fish survived to Chipps Island but were not detected because of tag expiration.

Although methods are available to adjust survival estimates for tag failure, the study team did not apply them. The team has found that survival estimates remain biased following adjustment because the adjustment relies on travel time distribution. In addition to creating a negative bias related to survival estimates, tag failure negatively biases the travel time distribution; fish with longer travel times are not detected. Therefore, the adjustment can account for some but not all tag failure.

Table 3.8-4
Survival and Route Entrainment Probabilities for BAFF On/Off Operations for Late Fall–Run Chinook Salmon Released in Spring 2011

BAFF Operation	Reach/Route	Survival Probability ($S_{h,n}$)		Route Entrainment Probability ($\Psi_{h,n}$)	
		Estimate (SE)	95% CI	Estimate (SE)	95% CI
NA	Release to array	0.957 (0.005)	0.946, 0.966	NA	
On	$S_{S,on}$	0.975 (0.006)	0.961, 0.985	0.926 (0.010)	0.905,0.944
Off	$S_{S,off}$	0.979 (0.006)	0.966, 0.989	0.779 (0.015)	0.749,0.808
On	$S_{G,on}$	0.961 (0.027)	0.884, 0.993	0.074 (0.010)	0.056,0.095
Off	$S_{G,off}$	0.927 (0.020)	0.881, 0.960	0.221 (0.015)	0.192,0.251
On	$S_{SC,on}$	0.654 (0.020)	0.613, 0.694	NA	NA
Off	$S_{SC,off}$	0.655 (0.021)	0.613, 0.697	NA	NA
On	$S_{GC,on}$	0.149 (0.052)	0.067, 0.268	NA	NA
Off	$S_{GC,off}$	0.190 (0.033)	0.132, 0.259	NA	NA
On	Total survival for Sacramento River	0.610 (0.020)	0.603, 0.616		
Off	Total survival for Sacramento River	0.614 (0.021)	0.607, 0.620		
On	Total survival for Georgiana Slough	0.137 (0.048)	0.135, 0.138		
Off	Total survival for Georgiana Slough	0.169 (0.029)	0.167, 0.170		

Notes: SE = standard error.

Survival was estimated from the release site to the array and from the start line of the array to peripheral hydrophones located in either the Sacramento River or Georgiana Slough. Confidence intervals (CIs) were estimated with profile likelihood methods.

The operation of the BAFF did not appear to influence survival of juvenile Chinook downstream of the study area. Survival for the BAFF On and BAFF Off conditions were not significantly different for either route, which suggests that operation of the BAFF did not have a negative effect on survival of fish downstream of the barrier. This finding is not surprising because operation of the BAFF would need to have a large localized effect on survival to considerably influence route-specific survival. Other studies have found an influence of behavioral stimuli on physiological responses of fish, which might in turn affect predation rates. Richards et al. (2007) reported increased cortisol levels in Chinook salmon when the fish were exposed to high-frequency strobe lights, but cortisol levels returned to normal several hours after the stimulus was removed. Flamarique et al. (2006) found that strobe lights could induce torpor in sockeye salmon (*Oncorhynchus nerka*). If excessive stress or torpor was induced by the BAFF, the study team would expect greater mortality for fish that encountered the BAFF in the on state, but such an effect was not observed.

The high flows in 2011 and the presence of hydrophones at Chipps Island provided the study team with a unique opportunity to assess fine-scale behavioral responses to the BAFF, as well as the potential effect of the BAFF on Delta-wide survival. Assessing Delta-wide survival should be a consideration in designing future telemetry studies of emigrating juvenile salmonids in the Delta because the ultimate goal of operating the BAFF is to increase Delta-wide survival.

Based on the results, with BAFF On, overall survival is (0.926*0.61) + (0.074*0.137) = 0.575. With BAFF Off, overall survival is (0.779*0.614) + (0.221*0.169) = 0.512. This is an 11percent relative improvement, not accounting for tag life differences. This addresses the issue noted by Perry et al. (2013), i.e., that changing routing only gives a modest change in survival if reach-specific survivals are not also changed (or different) between the routes.

4 INTEGRATION AND SYNTHESIS

An integration and synthesis of the results and findings of the 2012 GSNPB Study follow.

4.1 BARRIER EFFICIENCY AND ENTRAINMENT PROBABILITY

- During the March 6 through April 28 period of the 2012 study, 1,501 tagged juvenile Chinook salmon and 299 steelhead were released.

- Overall, during the 2012 tests, the BAFF reduced the percentage of Chinook salmon passing into Georgiana Slough from 24.8 percent when the BAFF was off to 10.3 percent when the BAFF was on, representing an overall reduction in entrainment into Georgiana Slough of 14.5 percentage points. The observed reduction in entrainment for juvenile Chinook salmon was statistically significant when the BAFF was on ($P=<0.0001$). This improvement produced an overall efficiency rate of 89.7 percent; that is, 89.7 percent of Chinook salmon that entered the area when the BAFF was on exited by continuing down the Sacramento River. The BAFF reduced the percentage of steelhead passing into Georgiana Slough from 25.6 percent when the BAFF was off to 12.3 percent when the BAFF was on, representing an overall reduction in entrainment into Georgiana Slough of 13.3 percentage points. The improvement produced an overall efficiency rate of 87.7 percent.

- Results of statistical analyses of survival and route entrainment probabilities (mark-recapture model) using the 2012 data showed that for juvenile Chinook salmon the probability of entering Georgiana Slough when the BAFF was on was 11.8 percent, whereas the probability increased to 24.4 percent when the BAFF was off. For juvenile steelhead, the probability of entering Georgiana Slough was 11.6 percent when the BAFF was on and 26.4 percent when the BAFF was off. The survival of juvenile salmon from the point of release to the BAFF (78.3 percent) was relatively low in 2012 and considerably lower (17.4 percentage points) than survival observed during the 2011 studies (95.7 percent), when river flow was greater. Survival from point of release to the BAFF for steelhead was also relatively low in 2012 (66.2 percent). Survival rates were higher for juvenile salmonids downstream of the BAFF in the Sacramento River and lower for those fish that migrated into Georgiana Slough.

- Deterrence efficiency when the BAFF was on was greater for juvenile steelhead (69.9 percent) than for juvenile Chinook salmon (56.1 percent), suggesting that steelhead were more strongly deterred than juvenile Chinook salmon by the BAFF. No statistically significant difference was detected in either protection or overall efficiency between juvenile salmon and steelhead when the BAFF was on, suggesting that operation of the BAFF provided consistent protection and overall efficiency for both salmonid species.

- Under low light levels (<5.4 lux) when the BAFF was on, deterrence efficiency was less for juvenile Chinook salmon (49.2 percent) when compared to steelhead (65.7 percent). Protection efficiency when the BAFF was on was also less for Chinook salmon (84.2 percent) when compared to steelhead (100 percent). Overall efficiency when the BAFF was on was found to be greater for steelhead (100 percent) than for Chinook salmon (84.2 percent). The same pattern in differences was observed between steelhead and Chinook salmon under high light levels (>5.4 lux) for deterrence and protection efficiency, with the exception of overall efficiency for steelhead (81.5 percent) was less than for Chinook salmon (95.0 percent), suggesting that steelhead may be more sensitive to the BAFF under low light conditions than under high light conditions.

- Under low approach velocity levels (<0.25 m/s) when the BAFF was on, deterrence efficiency was less for juvenile Chinook salmon (57.3 percent) when compared to steelhead (76.3 percent). Protection efficiency when the BAFF was on was slightly higher for Chinook salmon (94.5 percent) when compared to steelhead (92.9 percent). Overall efficiency when the BAFF was on was found to be greater for Chinook salmon (94.2 percent) than for steelhead (88.7 percent). Under high approach velocity levels (>0.25 m/s) when the BAFF was on, for deterrence, protection, and overall efficiency were higher for steelhead (57.1 percent, 100 percent, and 85.7 percent, respectively) than for Chinook salmon (48.5 percent, 51.5 percent, and 59.1 percent, respectively). Yearling steelhead were larger than juvenile Chinook salmon used in these tests and likely had greater swimming capability; this greater swimming capacity may have made it possible for steelhead to manoeuver away from the BAFF more effectively than Chinook salmon producing higher barrier efficiencies.

- A generalized linear model (GLM) of BAFF performance was developed for juvenile Chinook salmon based on the results of the 2012 experiments. The model considered the following covariates: barrier on/off, time of day (day vs. night), Sacramento River flow (cfs), cross-sectional location of each fish in the river channel, location of the critical streakline in the channel cross-section, and the location of the fish along the river axis. Model results for juvenile Chinook salmon suggested that cross-section position of the fish in the Sacramento River and BAFF operation had the largest effect on the probability of entrainment into Georgiana Slough, supporting the hypothesis that the BAFF operation affected migration route selection for juvenile Chinook salmon. The model also showed an influence of river flow on entrainment into Georgiana Slough, with greater entrainment risk as river flow increased. Turbidity and water temperature can co-vary with flow and the influence of these variables on route selection required further evaluation. Water velocity can also co-vary with flow; however, it is also strongly influenced by tide phase.

- Results of a similar GLM for juvenile steelhead suggested that river flow and cross-sectional position had the largest influence on entrainment risk, with other covariates, including BAFF operation, streakline location, along-stream location, and time of day, contributing less to the risk of entrainment. Similar to results for Chinook salmon, the steelhead model showed that the risk of entrainment into Georgiana Slough increased as river flow increased.

- As would be expected, both Chinook salmon and steelhead that migrated nearer to the Sacramento River channel bank that leads into Georgiana Slough had a higher probability of entrainment than those fish that migrate nearer to the opposite bank or mid-channel. BAFF operation contributed to a reduction in risk of entrainment for both Chinook salmon and steelhead, which is consistent with results of deterrence, protection, and overall efficiency tests in showing that BAFF operation contributed to a greater probability of juvenile salmonids remaining in the Sacramento River. The results showing that the cross-sectional location of juvenile salmonids in the Sacramento River channel is a major factor in determining entrainment risk support additional consideration of management actions and approaches that would help guide the migration pathway of juvenile salmonids away from the vicinity of Georgiana Slough and closer to the middle of the channel or opposite channel bank. The 2012 results suggest that even a small lateral movement of juvenile salmonids in the Sacramento River channel can have a substantial influence on reducing the risk of entrainment into Georgiana Slough. Other studies using floating log booms and guidance fences have shown that these relatively simple structures can be effective in changing the migration path of juvenile salmonids in river environments (Scott 2012).

- Results of the 2012 studies were also used to develop a route entrainment model of the response of juvenile salmonids to BAFF operations. Model results showed that under conditions of low Sacramento River flow there is a greater risk of entrainment regardless of BAFF operations. Although the probability of entrainment increased under low river flow conditions, the BAFF On condition reduced the risk of entrainment compared to the BAFF Off conditions. These results suggest that the effectiveness of the BAFF would increase as flows in the Sacramento River increase.
- These findings show how an integrated multisensory (i.e., light, sound, air bubbles) non-physical barrier was able to reduce, but not eliminate, the probability of juvenile salmonids being entrained into Georgiana Slough.

4.2 PREDATORS AND PREDATION

- Survival probability is one measure of the effect of predation on juvenile Chinook salmon and steelhead during their downstream migration through the study area assuming no mortality due to other causes such as disease. The survival probability for the Sacramento River reach between the point of fish release and the BAFF for juvenile Chinook salmon was 78 percent, suggesting that relatively high predation was occurring upstream of the BAFF. In contrast, the survival probability for Chinook salmon in the Sacramento River reach downstream of the BAFF was 93 percent when the BAFF was on and 93 percent when the BAFF was off, suggesting that survival, relative to predation, in this reach was independent of BAFF operation. Survival of juvenile Chinook salmon in Georgiana Slough downstream of the BAFF was 87 percent when the BAFF was on and 83 percent when the BAFF was off. These results are consistent with earlier survival studies which also showed higher survival and lower predation losses for juvenile Chinook salmon that migrate downstream in the Sacramento River. It is important to keep in mind that these results are limited to those relatively short reaches of the river and slough where acoustic monitoring was done as part of the 2012 study.
- Survival of juvenile steelhead in 2012 showed a pattern similar to that observed for juvenile Chinook salmon. Survival in the Sacramento River between the point of release and the BAFF was 66 percent, suggesting high predation rates on juvenile steelhead upstream of the BAFF. Survival in the Sacramento River reach downstream of the BAFF was 88 percent when the BAFF was on and 94 percent when the BAFF was off. Survival in Georgiana Slough downstream of the BAFF was 80 percent when the BAFF was on and 79 percent when the BAFF was off. As observed with juvenile Chinook salmon, predation mortality on juvenile steelhead was greater in the reach that included Georgiana Slough in 2012 compared to survival in the Sacramento River reach downstream of the BAFF.
- Based on analysis of tagged predator data, the following conclusions were made: The small differences in occupancy rates of tagged predators in different spatial scales and among the BAFF installed condition, BAFF not installed condition, and conditions combined suggest that the BAFF’s physical features had no effect on predator densities in the area immediately surrounding the BAFF. The apparent positive relationship in occupancy rate of tagged predators with increased distance from the BAFF during the BAFF On condition and the apparent negative relationship in occupancy rate with increased distance from the BAFF during the BAFF Off condition suggest predatory fish as a group showed avoidance behavior in response to the BAFF’s deterrence features. Predation rate spatial patterns across all comparisons suggest the BAFF’s physical and deterrence features did not contribute to increased predation in the area immediately surrounding the BAFF. It is important to note that predation rates in the study area during the study time period in the absence of a BAFF’s physical and deterrence features (i.e., true baseline predation rates) are unknown; therefore, results of

the study should be interpreted carefully. Predation rates in the entire study area may have been influenced by the presence and operation of the BAFF.

- Based on analysis of active hydroacoustics data, the BAFF operation appeared to have no impact on the average position of larger fish in the water column near the BAFF.

4.3 COMPARISON OF BAFF PERFORMANCE BETWEEN 2011 AND 2012 FOR JUVENILE CHINOOK SALMON

- Results of statistical analysis of the 2012 data showed that the percentage of juvenile Chinook salmon migrating into Georgiana Slough was reduced from 24.4 percent (BAFF Off) to 11.8 percent (BAFF On), a reduction of approximately one-half. During the 2011 study period, operation of the BAFF reduced the percentage of juvenile Chinook salmon passing into Georgiana Slough from 22.1 percent (BAFF Off) to 7.4 percent (BAFF On); a reduction of approximately two-thirds of the fish that would have been entrained. The magnitude of juvenile Chinook salmon migration into Georgiana Slough when the BAFF was off was similar between the two years as was the percentage reduction in the risk of entrainment into Georgiana Slough when the BAFF was on (a reduction of 12.6 percentage points in 2012 and 14.7 percentage points in 2011). In both years, operation of the BAFF contributed to a reduction in the movement of juvenile Chinook salmon from the Sacramento River into Georgiana Slough.

- Results of a comparison of the 2012 and 2011 studies using juvenile Chinook salmon found no statistically significant differences in deterrence efficiency, protection efficiency, or overall efficiency when the BAFF was on between the two years. The deterrence efficiency when the BAFF was on was 56.1 percent in 2012 and 50.4 percent in 2011. Protection efficiency when the BAFF was on was 89.0 percent in 2012 and 90.5 percent in 2011. Overall efficiency when the BAFF was on was 89.7 percent in 2012 and 90.8 percent in 2011. Similarly, no significant differences were detected in deterrence, protection, or overall efficiency when the BAFF was on under low and high light levels or during low and high water velocities between 2012 and 2011. These results suggest that despite the large differences in Sacramento River flows during the 2012 and 2011 surveys, operation of the BAFF provided consistent protection and overall efficiency in reducing the risk of juvenile Chinook salmon entrainment into Georgiana Slough.

- The estimated survival probability for juvenile Chinook salmon in the Sacramento River upstream of the BAFF (from point of release to the BAFF) in 2012 was 78.3 percent, which was 17.4 percentage points lower than the survival estimated in 2011 (95.7 percent. Flows and turbidity in the river were lower in 2012 compared to 2011, which may have contributed to greater predation mortality in the river upstream of the BAFF. It is hypothesized that high flows in the Sacramento River and corresponding increased water velocities and turbidity levels may have contributed to the relatively low level of predation on juvenile Chinook salmon estimated during the 2011 tests. Based on the similarity between estimates of protection and overall efficiency observed in both the 2012 and 2011 studies, the effects of predation on juvenile Chinook salmon in the immediate vicinity and downstream of the BAFF were low.

- Analysis using GLM for both the 2012 and 2011 study results found that river discharge, which is a function of velocity, the cross-sectional location of the fish in the Sacramento River, and BAFF operations, were important predictors of fish behavioral response to the BAFF and entrainment into Georgiana Slough in both years of the study.

- Results of the 2012 tests showed that at substantially lower Sacramento River flow rates, BAFF operation consistently reduced the probability that juvenile Chinook salmon would be entrained into Georgiana Slough. Simulation model results using the 2012 test data showed that under very low Sacramento River flows, tidally driven reverse flow into Georgiana Slough increases the risk of juvenile Chinook salmon entrainment, although operation of the BAFF is predicted to reduce this risk. Under relatively high river flows during the 2011 tests (approximately 43,000-45,000 cfs river flow entering the river junction at Georgiana Slough), operation of the BAFF also consistently reduced the probability that juvenile Chinook salmon would be entrained into Georgiana Slough.

- The interaction of the cross-sectional position of the fish with river flow was the predominant factor that influenced the risk of juvenile salmonids entrainment into Georgiana Slough. Under the GLM, the location of a fish in the river channel cross section was the most important driver of an individual fish's probability of entrainment into Georgiana Slough in both 2012 and 2011. Under conditions of relatively lower river flow and velocity in 2012 (compared to 2011), juvenile salmonids may have a greater opportunity to respond to the BAFF and flows entering Georgiana Slough, although results of the 2012 study were consistent with those from 2011 in showing that the location of fish in the river channel is a strong influence on the risk of entrainment into Georgiana Slough. Under the high flow (and high-velocity) conditions in 2011, operation of the BAFF was less effective for fish located close to the east side of the river channel (downstream river left). These results suggest that fish in this area cannot behaviorally respond to the BAFF and swim away from it fast enough under high river flow conditions to avoid being swept across the barrier and into Georgiana Slough.

- Although varying light conditions did not appear to affect juvenile salmonid entrainment into Georgiana Slough or BAFF efficiency results, turbidity levels were relatively low during the 2012 study period and high during the 2011 study period. High turbidity in 2011 likely muted the BAFF's light intensity and limited the use of visual cues for juvenile salmonids to be guided by the BAFF during the daytime. This muting may have led to similar performance between daytime and nighttime tests; however, results of the 2012 study, under lower turbidity conditions showed a pattern similar to that from the 2011 study.

- Results from the 2012 study showed similar protection and overall efficiency estimates with the BAFF on and off, as well as no relationship between BAFF operation and survival in the Sacramento River and Georgiana Slough. In 2011, the analyses showed similar protection and overall efficiency rates to 2012 under both BAFF On and BAFF Off conditions. Additionally, survival estimates for juvenile Chinook salmon observed in both Georgiana Slough and the Sacramento River were similar and not significantly different under BAFF On and BAFF Off conditions.

- Acoustic telemetry data indicated that predators were located primarily near the river margin, which reduced the rate of encounters with juvenile salmonids that tended to migrate closer to the center of the channel. The relatively low Sacramento River discharges of 2012 may have provided a different bioenergetic landscape than occurred under higher flow conditions in 2011. Estimates of the probability of survival for juvenile salmonids in the river upstream of the BAFF showed higher predation mortality when flows were lower in 2012 compared to the higher flow conditions in 2011. River flow typically co-varies with other physical environmental variables, including turbidity and water temperature, which may be the functional reason for lower predation at higher flows (e.g., reduced ability to see prey (associated with higher turbidity), and reduced metabolic requirements (associated with reduced temperatures).

- It has been hypothesized that a non-physical barrier such as the BAFF may attract predatory fish, thus increasing predation mortality for juvenile salmonids. To examine this hypothesis, predation frequencies were estimated for areas within 5 m of the BAFF and compared to predation rates farther from the BAFF in the Sacramento River. The results do not support the hypothesis that presence of the BAFF increases predation mortality for juvenile salmonids in the immediate vicinity of the non-physical barrier. The similarity between protection and overall efficiency observed in the 2012 studies when the BAFF was on and off supports the findings of the 2011 studies, which showed that one predation event occurred within 5 m of the BAFF and 48 events occurred in the larger array area. It is important to note that if the BAFF were to be used as a long-term management tool, predators could become conditioned to the operation of the BAFF which may allow them to alter their behavior from what was observed in the 2012 and 2011 studies. In addition, the habitat selected by predators and the movement patterns of predators, in the Sacramento River adjacent to the BAFF might vary within and among years in response to factors such as river flow and velocities, water temperatures, and recreational harvest. These factors, in combination with possible conditioning to BAFF operations, could result in different predation rates than those observed during the 2012 and 2011 studies.

4.4 2011 DELTA-WIDE SURVIVAL

- The operation of the BAFF did not appear to influence survival of juvenile Chinook below the study area. Survival for the BAFF On and BAFF Off conditions were not significantly different for either route, which suggests that operation of the BAFF did not have a negative effect on survival of fish downstream of the barrier. This finding is not surprising because operation of the BAFF would need to have a large localized effect on survival to considerably influence route-specific survival. Other studies have found an influence of behavioral stimuli on physiological responses of fish, which might in turn affect predation rates. Richards et al. (2007) reported increased cortisol levels in Chinook salmon when the fish were exposed to high-frequency strobe lights, but cortisol levels returned to normal several hours after the stimulus was removed. Flamarique et al. (2006) found that strobe lights could induce torpor in sockeye salmon (*Oncorhynchus nerka*). If excessive stress or torpor was induced by the BAFF, the study team would expect greater mortality for fish that encountered the BAFF in the on state, but such an effect was not observed.

- Survival estimates for fish migrating through the Sacramento River in 2011 were 0.610 and 0.614 and estimates for fish migrating through Georgiana Slough were 0.137 and 0.169. Estimates for the Sacramento River (0.610 and 0.614) are higher than estimates from Perry et al. (2010) (0.443 to 0.564) and Perry et al. (2012) (0.485 to 0.584). Conversely, the study team's estimates for fish migrating through Georgiana Slough (0.137 and 0.169) are lower than estimates by Perry et al. (2010) (0.332 to 0.344) and Perry et al. (2012) (0.179 to 0.314). It is important to note that even with relatively quick travel times, the travel times for a portion of fish moving through both migration routes exceeded estimated tag life. Therefore, the survival estimates provided are likely to be negatively biased.

- Based on the results, with BAFF On, overall survival is (0.926*0.61) + (0.074*0.137) = 0.575. With BAFF Off, overall survival is (0.779*0.614) + (0.221*0.169) = 0.512. This is an 11 percent relative improvement, not accounting for tag life differences. This addresses the issue noted by Perry et al. (2013), i.e., that changing routing only gives a modest change in survival if reach-specific survivals are not also changed (or different) between the routes.

5 STUDY CONCLUSIONS

The results of the 2012 tests showed that when the BAFF was on there were statistically significant increases in deterrence, protection, and overall efficiency for juvenile Chinook salmon and steelhead; that is, fewer of the tagged Chinook salmon and steelhead migrated into Georgiana Slough when the BAFF was on than when it was off. For example, an approximately 52 percent reduction in entrainment into Georgiana Slough was accomplished when the BAFF was on (11.8 percent) compared to when it was off (24.4 percent) for juvenile Chinook salmon in 2012, with a similar reduction observed for steelhead when the BAFF was on (10.5 percent) and when it was off (23.4 percent). The reduction in the probability that juvenile salmon would migrate into Georgiana Slough was similar to the results of the 2011 study. The cross-sectional location of fish in the Sacramento River channel when migrating past Georgiana Slough, river flow, and BAFF operation were found to be important factors influencing the probability that a juvenile Chinook salmon or steelhead would migrate from the Sacramento River into Georgiana Slough during both the 2012 and 2011 studies. Overall, based on a variety of alternative methods and metrics for data analysis, the results of the studies conducted in 2012 and 2011 over a range of Sacramento River flow conditions consistently showed that operation of the BAFF contributed to a reduction in the migration of juvenile salmonids into Georgiana Slough. It is concluded that operation of the BAFF would be likely to result in an incremental increase in through-Delta survival of emigrating Sacramento River juvenile salmonids. The study design for the 2012 and 2011 tests did not include acoustic tag monitoring downstream at Chipps Island or the Golden Gate; therefore, the contribution of operating the BAFF to juvenile salmonid survival through these reaches could not be estimated.

This page intentionally left blank.

6 RECOMMENDATIONS AND FUTURE DIRECTIONS

It is recommended that the results of the 2011 and 2012 studies, and expected performance of the BAFF in increasing juvenile salmonid survival, be evaluated in context with a lifecycle population dynamics model and/or Delta passage survival model (examples of this type of analysis have been partially performed as part of the Bay Delta Conservation Plan). NMFS is developing a lifecycle model for Sacramento River winter-run Chinook salmon that could potentially be used to assess the incremental contribution of a reduction in juvenile salmon migration into the interior Delta. In addition, the Delta Passage Model (DPM) is used to assess the effects of changes in water project operation and hydrodynamics on survival of juvenile Chinook salmon migrating through the lower Sacramento River and Delta. The lifecycle model could be used to assess the effectiveness of BAFF operations in reducing the risk of incidental take of juvenile salmonids at the south Delta export facilities. It also could be used to assess the incremental contribution of operating the BAFF to the survival and abundance of Chinook salmon. Modeling (e.g., DPM) would also allow an assessment of the BAFF's contributions to increasing juvenile salmon survival during emigration from the Sacramento River, and the population benefits of improved guidance and reduced mortality on juvenile salmon. Finally, lifecycle modeling could determine whether the BAFF might contribute, and to what extent, to increased adult abundance, species protection, and recovery of listed Sacramento River Chinook salmon and Central Valley steelhead populations. Efforts are also underway to conduct additional studies on the route selection, survival, risk of predation, and response to tidal and hydrodynamic conditions of juvenile salmonids. These studies are intended to complement and support additional testing and analysis of the biological benefits to Chinook salmon and steelhead from management actions such as those undertaken at Georgiana Slough.

Based on the extensive body of information developed through the 2011 and 2012 studies, it is recommended that no additional BAFF testing be conducted at Georgiana Slough using the barrier configuration tested in 2011 and 2012. Results of the two years of study, in combination with statistical and simulation models that have been developed, could be used to refine and optimize the BAFF configuration and location, which would be subject to additional testing. Operation of the BAFF contributed to reduced entrainment into Georgiana Slough in both 2011 (during high-flow conditions) and 2012 (during lower flow conditions). However, the capital, operating, and maintenance costs of the BAFF are relatively high; installation and maintenance can be difficult during high flow conditions; the BAFF is a complex facility requiring substantial staff resources for operations; and reliable operation under variable conditions inherent in the Sacramento River should be carefully evaluated before a permanent installation is considered.

As an alternative (or supplement) to the BAFF, it is recommended that consideration be given to testing a floating fish guidance structure (floating boom-type structure) in 2014 (possibly in combination with an optimized BAFF configuration and operation). Like the BAFF, it would be used to prevent juvenile salmonids in the Sacramento River from entering Georgiana Slough. Similar fish guidance systems have been tested and proven to be effective for juvenile salmonids in other West Coast river systems. Results of both the 2011 and 2012 tests are consistent in showing that relatively small changes in the cross-sectional location of juvenile salmonids in the Sacramento River channel upstream of Georgiana Slough could contribute to substantial reductions in the risk that juvenile Chinook salmon and steelhead will migrate from the Sacramento River into the interior Delta via Georgiana Slough.

This page intentionally left blank.

7 REFERENCES

Adams, N. S., D. W. Rondorf, S. D. Evans, and J. E. Kelly. 1998. Effects of Surgically and Gastrically Implanted Radio Transmitters on Growth and Feeding Behavior of Juvenile Chinook Salmon. *Transactions of the American Fisheries Society* 127:128–136.

Anderson, J. J., K. J. Puckett, and R. S. Nemeth. 1988. *Studies on the Effect of Behavior on Fish Guidance Efficiency at Rocky Reach Dam: Avoidance to Strobe Light and Other Stimuli.* Final Report for Chelan County Public Utility District No. 1. Fisheries Research Institute FRI-UW-8801. Seattle: University of Washington.

Austin, D., Bowen W. D., and McMillan J. I. 2004. Intraspecific Variation in Movement Patterns: Modeling Individual Behaviour in a Large Marine Predator. *Oikos* 105:15–30.

Bartumeus, F., M. G. E. da Luz, G. M. Viswanathan, and J. Catalan. 2005. Animal Search Strategies: A Quantitative Randomwalk Analysis. *Ecology* 86:3078–3087.

Beamish, F. W. H. 1978. Swimming Capacity. In *Fish Physiology*, Volume VII, ed. W. H. Hoar and D. J. Randall, 101–187. New York: Academic Press.

Beaumont, William. Game & Wildlife Conservation Trust, Wareham, Dorset, United Kingdom. 2011—e-mail to Andy Turnpenny, Fish Guidance Systems, Southampton, Hampshire County, United Kingdom.

Benaglia, T., D. Chauveau, D. R. Hunter, and D. S. Young. 2009. Mixtools: An R Package for Analyzing Finite Mixture Models. *Journal of Statistical Software* 32:1–29.

Benhamou, S. 2004. How to Reliably Estimate the Tortuosity of an Animal's Path: Straightness, Sinuosity, or Fractal Dimension? *Journal of Theoretical Biology* 229:209–220.

Blackman, S. 1986. *Multiple Target Tracking with Radar Applications*. Artech House, Massachusetts.

Blake, A., and M. Horn. 2006. *Acoustic Tracking of Juvenile Chinook Salmon Movement in the Vicinity of Georgiana Slough, Sacramento River, California–2003 Study Results*. Draft report. Sacramento, CA: U.S. Geological Survey.

Bowen, M. D., and R. Bark. 2012. *2010 Effectiveness of a Non-Physical Fish Barrier at the Divergence of the Old and San Joaquin Rivers (CA).* Technical Memorandum 86-68290-10-07. Denver: U.S. Bureau of Reclamation.

Bowen, M. D., S. Hiebert, C. Hueth, and V. Maisonneuve. 2012 (September). *2009 Effectiveness of a Non-Physical Fish Barrier at the Divergence of the Old and San Joaquin Rivers (CA)*. Technical Memorandum 86-68290-09-05. Denver: U.S. Bureau of Reclamation.

Bowker, J., and J. Trushenski. 2011. AFS Policy Statement Regarding the Need for an Immediate-Release Anesthetic/Sedative for Use in the Fisheries Disciplines. *Fisheries* 36(3):132–135.

Bozek, M. A, P. H. Short, C. J. Edwards, M. J. Jennings, and S. P. Newman. 2002. *Habitat selection of nesting smallmouth bass* Micropterus dolomieu *in two north temperate lakes.* American Fisheries Society Symposium 31:135-148.

Bradford, M. J., and P. S. Higgins. 2001. Habitat-, Season-, and Size-Specific Variation in Diel Activity Patterns of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead Trout (*Oncorhynchus mykiss*). *Canadian Journal of Fisheries and Aquatic Sciences* 58:365–374.

Brandes, P. L., and J. S. McLain. 2001. Juvenile Chinook Salmon Abundance, Distribution, and Survival in the Sacramento–San Joaquin Estuary. In *Contributions to the Biology of Central Valley Salmonids*, Fish Bulletin 179, Volume 2, ed. R. L. Brown, 39–136. Sacramento: California Department of Fish and Game.

Brett, J. R. 1952. Temperature Tolerance in Young Pacific Salmon, Genus Oncorhynchus. *Journal of the Fisheries Research Board of Canada* 9:265–323.

Brown, L. R. 1990. Age, Growth, Feeding, and Behavior of Sacramento Squawfish (*Ptychocheilus grandis*) in Bear Creek, Colusa Co., California. *The Southwestern Naturalist* 35:249–260.

Burwen, D. L., S. J. Fleischman, and J. D. Miller. 2007. *Evaluation of dual-frequency imaging sonar for estimating fish size in the Kenai River*. Alaska Department of Fish and Game, Fishery Data Series No. 07 44, Anchorage, AK.

California Department of Fish and Game. 2007. Vegetation and Land Use Mapping of the Sacramento–San Joaquin Delta for the Vegetation Classification and Mapping Program (VegCAMP). Available: http://www.dfg.ca.gov/biogeodata/vegcamp/.

California Department of Water Resources. 2012. *2011 Georgiana Slough Non-Physical Barrier Performance Evaluation Project Report*. Bay-Delta Office. Sacramento, CA.

California Irrigation Management Information System. 2011. Statewide Integrated Pest Management Program, 2011. California Weather Data for CIMIS Station 140, Twitchell Island. University of California, Department of Agriculture and Natural Resources. Davis, CA.

Chapman, E., A. Hearn, C. Michel, A. Ammann, S. Lindley, M. Thomas, P. Sandstrom, G. Singer, M. Peterson, R. B. MacFarlane, and A. P. Klimley. 2013. Diel Movements of Out-Migrating Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead Trout (*Oncorhynchus mykiss*) Smolts in the Sacramento/San Joaquin Watershed. *Environmental Biology of Fishes* 96:273–286.

CIMIS. *See* California Irrigation Management Information System.

Coutant, C. C. 2001. Integrated, Multi-Sensory, Behavioral Guidance Systems for Fish Diversions. In *Behavioral Technologies for Fish Guidance*, ed. C. C. Coutant, 105–114. American Fisheries Society, Symposium 26, Bethesda, MD.

Coyle, S. D., R. M. Duborow, and J. H. Tidwell. 2004. *Anesthetics in Aquaculture*. U.S. Department of Agriculture, Southern Regional Aquaculture Center, Publication No. 3900.

DWR. *See* California Department of Water Resources.

Ehrenberg, J. E., and T. W. Steig. 2003. Improved Techniques for Studying the Temporal and Spatial Behavior of Fish in a Fixed Location. *ICES Journal of Marine Science* 60:700–706.

Ehrenberg, J. E., and T. W. Steig. 2009. A Study of the Relationship between Tag-Signal Characteristics and Achievable Performances in Acoustic Fish-Tag Studies. *ICES Journal of Marine Science* 66:1278–1283.

Fayram, A. H., and T. H. Sibley T. H. 2000. Impact of Predation by Smallmouth Bass on Sockeye Salmon in Lake Washington, Washington. *North American Journal of Fisheries Management* 20:81–89.

Flamarique, I. N., S. Hiebert, and J. Sechrist. 2006. Visual Performance and the Ocular System Structure of Kokanee and Sockeye Salmon Following Strobe Light Exposure. *North American Journal of Fisheries Management* 26:453–459.

FSA. See. U.S. Farm Service Agency.

Gurarie, E. 2008. Models and Analysis of Animal Movements: From Individual Tracks to Mass Dispersal. Ph.D. dissertation. University of Washington. Seattle, WA.

Halvorsen, M. B., L. E. Wysocki, C. M. Stehr, D. H. Baldwin, D. R. Chicoine, N. L. Scholz, and A. N. Popper. 2009. Barging Effects on Sensory Systems of Chinook Salmon Smolts. *Transactions American Fisheries Society* 138:777–789.

Hanson, C. H. 2009. *Striped Bass Predation on Listed Fish within the Bay Delta Estuary and Tributary Rivers.* Expert report in *Coalition for a Sustainable Delta et al. v. McCamman*.

Horn, M. J., and A. Blake. 2004 (February). *Acoustic Tracking of Juvenile Chinook Salmon Movement in the Vicinity of the Delta Cross Channel. 2001 Study Results*. USBR Technical Memorandum No. 8220-04-04. Denver, CO: Technical Service Center.

Hosmer, D. W., and S. Lemeshow. 2000. *Applied Logistic Regression*. New York: John Wiley and Sons.

Ibbotson, A. T., W. R. C. Beaumont, A. Pinder, S. Welton, and M. Ladle. 2006. Diel Migration Patterns of Atlantic Salmon Smolts with Particular Reference to the Absence of Crepuscular Migration. *Ecology of Freshwater Fish* 15:544–551.

Itazawa, Y., and T. Takeda. 1982. Respiration of Carp under Anesthesia Induced by Mixed Bubbling of Carbon Dioxide and Oxygen. *Bulletin of the Japanese Society of Science and Fisheries* 48(4):489–493.

Iwama, G. K., and P. A. Ackerman. 1994. Anesthesia. In *Biochemistry and Molecular Biology of Fishes*, Volume 3. eds. P. W. Hochachka and T.P. Mommsen, 1–15. Amsterdam: Elsevier Science B.V.

Kerstetter, D. W., J. Polovina, and J. E. Graves. 2004. Evidence of Shark Predation and Scavenging on Fishes Equipped with Pop-Up Satellite Archival Tags. *Fishery Bulletin* 102:750–756.

Kubacki, M. F., F. J. S. Phelan, J. E. Claussen, and D. P. Philipp. 2002. *How well does a closed season protect spawning bass in Ontario?* American Fisheries Society Symposium 31:379-386.

Lady, J. M., P. Westhagen, and J. R. Skalski. 2008. *USER 4: User Specified Estimation Routine*. School of Aquatic and Fishery Sciences, University of Washington. Available: http://www.cbr.washington.edu/paramest/user/. Accessed August 2011.

Liedtke, T. L., J. W. Beeman, and L. P. Gee. 2012. *A Standard Operating Procedure for the Surgical Implantation of Transmitters in Juvenile Salmonids*. U.S. Geological Survey Open-File Report 2012-1267.

Liedtke, T. L., and A. M. Wargo-Rub. 2012. Techniques for Telemetry Transmitter Attachment and Evaluation of Transmitter Effects on Fish Performance. In *Telemetry Techniques*, eds. N. Adams, J. Beeman, and J. Eiler. Bethesda, MD: American Fisheries Society.

Lyons, J. and P. Kanehl. 2002. *Seasonal movements of smallmouth bass in streams.* American Fisheries Society Symposium 31:149-160.

Martinelli, T. L., H. C. Hansel, and R. S. Shively. 1998. Growth and Physiological Responses to Surgical and Gastric Radio Transmitter Implantation Techniques in Subyearling Chinook Salmon (*Oncorhynchus tshawytscha*). *Hydrobiologia* 371/372:79–87.

Mather, M. E. 1998. The Role of Context-Specific Predation in Understanding Patterns Exhibited by Anadromous Salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 55:232–246.

Melnychuk, M. C., D. W. Welch, and C. J. Walters. 2010. Spatio-Temporal Migration Patterns of Pacific Salmon Smolts in Rivers and Coastal Marine Waters. PLOS ONE 5:e12916. Available: http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0012916.

Moyle, P. B. 2002. *Inland Fishes of California*. Revised and expanded. 2nd edition. Berkeley: University of California Press.

Myrick, C.A. and J.J. Cech. 2001. *Temperature effects on Chinook salmon and steelhead: a review focusing on California's Central Valley populations.* California Water and Environmental Modeling Forum. Available at http://www.sfei.org/modeling forum.

National Marine Fisheries Service. 2009 (June 4). *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. Long Beach, CA: Southwest Regional Office.

NMFS. *See* National Marine Fisheries Service.

Nobriga, M. L., and F. Feyrer. 2007. Shallow-Water Piscivore-Prey Dynamics in California's Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 5(2):Article 4.

Nobriga M. L., F. Feyrer F, and R. D. Baxter. 2006. Aspects of Sacramento Pikeminnow Biology in Nearshore Habitats of the Sacramento–San Joaquin Delta. *Western North American Naturalist* 66:106–114.

Orth, D. J. and T. J. Newcomb. 2002. *Certainties and uncertainties in defining essential habitats for riverine smallmouth bass.* American Fisheries Society Symposium 31:251-264.

Oxman, D. S., R. Barnett-Johnson, M. E. Smith, A. Coffin, D. L. Miller, R. Josephson, and A. N. Popper. 2007. The Effect of Vaterite Deposition on Sound Reception, Otolith Morphology, and Inner Ear Sensory Epithelia in Hatchery-Reared Chinook Salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences* 64:1469–1478.

Patrick, P. H., A. E. Christie, D. Sager, C. Hocutt, and J. Stauffer Jr. 1985. Response of Fish to a Strobe Light/Air-Bubble Barrier. *Fisheries Research* 3:157–172.

Perry, R. W. 2010. *Survival and Migration Dynamics of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in the Sacramento–San Joaquin River Delta.* Ph.D. dissertation. University of Washington. Seattle, WA.

Perry, R. W., J. G. Romine, S. J. Brewer, P. E. LaCivita, W. N. Brostoff, and E. D. Chapman. 2012. *Survival and migration route probabilities of juvenile Chinook salmon in the Sacramento-San Joaquin River Delta during the winter of 2009–10*: U.S. Geological Survey Open-File Report 2012-1200. U.S. Geological Survey, Reston, VA.

Perry, R. W., P. L. Brandes, J. R. Burau, A. P. Klimley, B. MacFarlane, C. Michel, and J. R. Skalski. 2013. Sensitivity of Survival to Migration Routes Used by Juvenile Chinook Salmon to Negotiate the Sacramento-San Joaquin River Delta. *Environmental Biology of Fishes* 96:381–392.

Perry, R. W., J. G. Romine, S. J. Brewer, P. E. LaCivita, W. N. Brostoff, and E. D. Chapman. 2012. *Survival and Migration Route Probabilities of Juvenile Chinook Salmon in the Sacramento–San Joaquin River Delta during the Winter of 2009–10*. U.S. Geological Survey Open-File Report 2012-1200.

Perry, R. W., J. R. Skalski, P. L. Brandes, P. T. Sandstrom, A. P. Klimley, A. Ammann, and B. MacFarlane. 2010. Estimating Survival and Migration Route Probabilities of Juvenile Chinook Salmon in the Sacramento–San Joaquin River Delta. *North American Journal of Fisheries Management* 30:142–156.

Plumb, J. M., N. S. Adams, and D. W. Rondorf. 1999. *Behavior of Juvenile Chinook Salmon and Steelhead Relative to the Log Boom at Lower Granite Dam*. Portland, OR: U.S. Army Corps of Engineers.

R Development Core Team. 2011. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria.

Rainey, W. S. 1985. *Considerations in the Design of Juvenile Bypass Systems.* In Proceedings of the Symposium on Small Hydropower and Fisheries, May 1–3, 1985, Aurora, CO, 261–268. Bethesda, MD: American Fisheries Society.

Richards, N. S., S. R. Chipps, and M. L. Brown. 2007. Stress Response and Avoidance Behavior of Fishes as Influenced by High-Frequency Strobe Lights. *North American Journal of Fisheries Management* 27:1310–1315.

San Joaquin River Group Authority. 2013. *2011 Annual Technical Report: On Implementation and Monitoring of the San Joaquin River Agreement and the Vernalis Adaptive Management Plan (VAMP)*. Modesto, CA. Prepared for California Water Resource Control Board. Available: http://www.sjrg.org/technicalreport.

San Luis & Delta-Mendota Water Authority and C. H. Hanson. 1996 (May). *Georgiana Slough Acoustic Barrier Applied Research Project: Results of 1994 Phase II Field Tests*. Technical Report 44. Interagency Ecological Program for the San Francisco Bay/Delta Estuary. Prepared for California Department of Water Resources and U.S. Bureau of Reclamation.

Scott, S. 2012. *A positive barrier fish guidance system design to improve safe downstream passage of anadromous fish*. Presented at the 9th ISE, Vienna.

Sims, D. W., E. J. Southall, N. E. Humphries, G. C. Hays, C. J. A. Bradshaw, J. W. Pitchford, A. James, M. Z. Ahmed, A. S. Brierley, M. A. Hindell, D. Morritt, M. K. Musyl, D. Righton, E. L. C. Shepard, V. J. Wearmouth, R. P. Wilson, M. J. Witt, and J. D. Metcalfe. 2008. Scaling Laws of Marine Predator Search Behaviour. *Nature* 451:1098–1102.

SJRGA. *See* San Joaquin River Group Authority.

Skalski, J. R., R. Townsend, J. Lady, A. E. Giorgi, J. R. Stevenson, and R. D. McDonald. 2002. Estimating Route-Specific Passage and Survival Probabilities at a Hydroelectric Project from Smolt Radiotelemetry Studies. *Canadian Journal of Fisheries and Aquatic Sciences* 59:1385–1393.

Sladky, K. K., C. R. Swanson, M. K. Stoskopf, M. R. Loomis, and G. A. Lewbart. 2001. Comparative Efficacy of Tricaine Methanesulfonate and Clove Oil for Use as Anesthetics in Red Pacu (*Piaractus brachypomus*). *American Journal of Veterinary Research* 62(3):337–342.

SLDMWA and Hanson. *See* San Luis & Delta-Mendota Water Authority and C. H. Hanson.

Stevens, D. E. 1966. Food Habits of Striped Bass, *Roccus saxatilis,* in the Sacramento–San Joaquin Delta. In *Ecological Studies of the Sacramento–San Joaquin Delta, Part II: Fishes of the Delta*, Fish Bulletin 136, comps. J. L. Turner and D. W. Kelley, 68–96. Sacramento: California Department of Fish and Game.

Svendsen, J. C., K. Aarestrup, H. Malte, U. H. Thygesen, H. Baktoft, A. Koed, M. G. Deacon, K. F. Cubitt, and R. S. McKinley 2011. Linking Individual Behaviour and Migration Success in *Salmo salar* Smolts Approaching a Water Withdrawal Site: Implications for Management. *Aquatic Living Resources* 24:201–209.

Swanson. C., P. S. Young, and J. J. Cech, Jr. 2004. Swimming in Two-Vector Flows: Performance and Behavior of Juvenile Chinook Salmon Near a Simulated Screened Water Diversion. *Transactions of the American Fisheries Society* 133:265–278.

Tabor, R. A., S. T. Sanders, M. T. Celedonia, D. W. Lantz, S. Damm, T. M. Lee, Z Li, and B. E. Price. 2010. *Spring/Summer Habitat Use and Seasonal Movement Patterns of Predatory Fishes in the Lake Washington Ship Canal*. Report to Seattle Public Utilities. Lacey, WA: U.S. Fish and Wildlife Service, Western Washington Fish and Wildlife Office.

Turnpenny, A. W. H., and N. O'Keeffe. 2005. *Screening for Intake and Outfalls: A Best Practice Guide.* Science Report SC030231. Environment Agency. Bristol, UK.

Welton, J.S., W.R.C Beaumont, and R.T. Clarke. 2002. The efficacy of air, sound and acoustic bubble screens in deflecting Atlantic salmon, *Salmo salar* L., smolts in the River Frome, UK. *Fisheries Management and Ecology* 9: 11-18. Article first published online: 25 JAN 2002 | DOI: 10.1046/j.1365-2400.2002.00252.x.

U.S. Farm Service Agency. 2012. One-Meter Color Aerial Imagery Acquired in the National Agriculture Imagery Program (NAIP) for San Joaquin County, California. Available: http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai.

Viswanathan, G. M., V. Afanasyev, S.V. Buldyrev, S. Havlin, M.G.E. da Luz, E. P. Raposo, and H. E. Stanley. 2000. Lévy Flights in Random Searches. *Physica A* 282:1–12.

Vogel, D.A. 2011 (October). Evaluation of Acoustic-Tagged Juvenile Chinook Salmon and Predatory Fish Movements in the Sacramento–San Joaquin Delta during the 2010 Vernalis Adaptive Management Program. Natural Resource Scientists, Inc.

Vogel, D. A. 2012. *Predatory fish movements and mobile telemetry results from a fish acoustic telemetry study conducted in the northern Sacramento – San Joaquin Delta, 2008-2009*. 54 pp. Natural Resource Scientists, Inc., Red Bluff, CA.

Vogel, D. A., and K. R. Marine. 1991. *Central Valley Project: Guide to Upper Sacramento River Chinook Salmon Life History.* Redding, CA: CH2M HILL. Prepared for U.S. Bureau of Reclamation.

Ward, E. J. 2008. A Review and Comparison of Four Commonly Used Bayesian and Maximum Likelihood Model Selection Tools. *Ecological Modeling* 211:1–10.

Webb, M. 2011. *Rangitata Diversion Race Bio-Acoustic Fish Fence Progress Report, 2010/11 Season*. Central South Island Fish and Game Report. Temuka, NZ.

Welton, J. S., W. R. C. Beaumont, and R. T. Clarke. 2002. The Efficacy of Air, Sound and Acoustic Bubble Screens in Deflecting Atlantic Salmon, *Salmo salar* L., Smolts in the River Frome, UK. *Fisheries Management and Ecology* 9:11–18.

This page intentionally left blank.