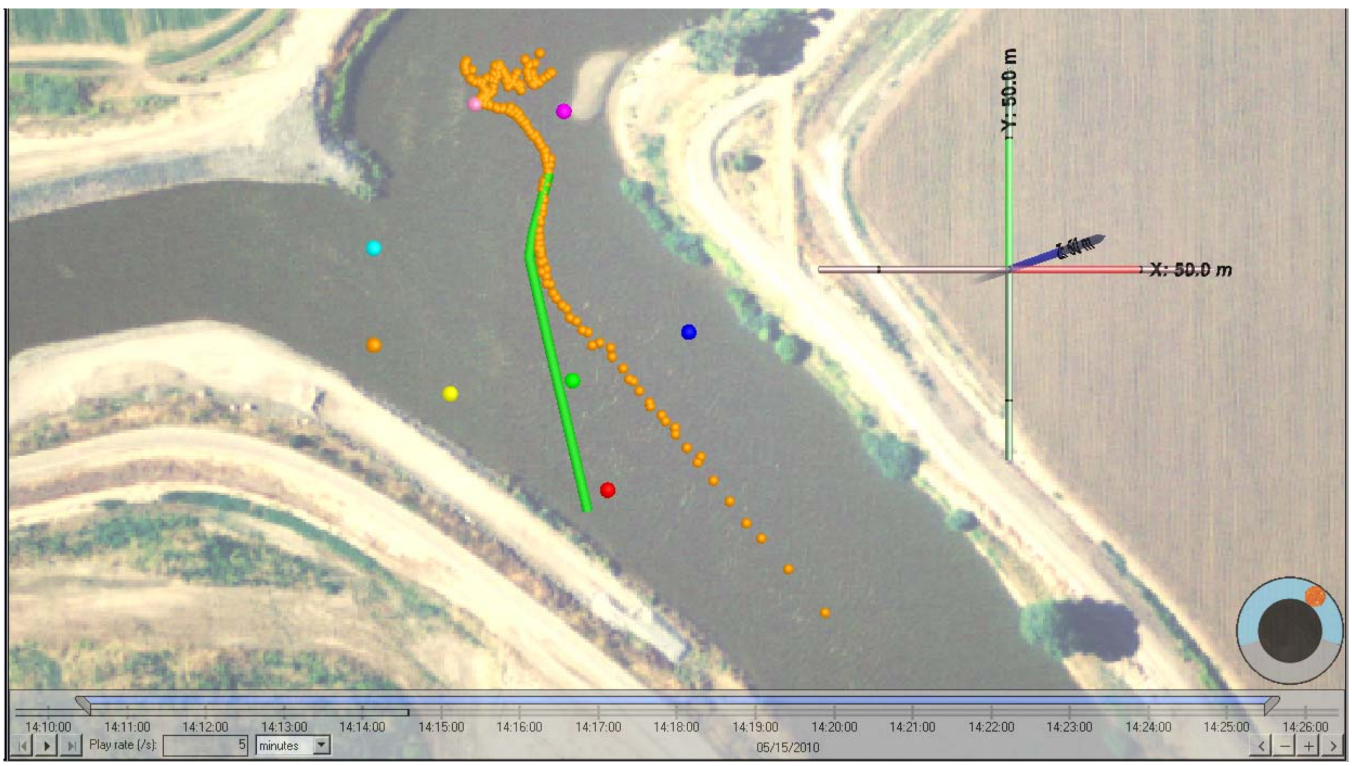
RECLAMATION

Managing Water in the West

Technical Memorandum 86-68290-10-07

2010 Effectiveness of a Non-Physical Fish Barrier at the Divergence of the Old and San Joaquin Rivers (CA)



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

April 2012

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

On the cover – *Double Predation* – Smolt 8073 was successfully deterred by the barrier on 5/15/10 at 14:13 hr.

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All sections were reviewed to certify the document meets Reclamation policy and professional standards for the fisheries biology field.

REVIEW CERTIFICATION

Peer Reviewer - I have reviewed the assigned Items/Section(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer: [signature] Review Date: 10/1/10
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Reviewer: ____________ Review Date: ____________
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Preparer - I have discussed the above document and review requirements with th Peer Reviewer and believe that this review is completed, and that the document will meet the requirements of the project.

Team Member: ____________ Date: ____________
Signature

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Acronyms

2D	2-dimensional
BAFF	Bio-Acoustic Fish Fence
Delta	Sacramento-San Joaquin Rivers Delta
DIDSO	Dual-frequency Identification Sonar
Divergence	deployed upstream of the divergence
FGS	Fish Guidance Systems
HTI	Hydroacoustic Technology, Inc
LED	light-emitting diode
O	overall efficiency
OR	Old River
ORB	Old River Barrier
Reclamation	Bureau of Reclamation
SAS	Statistical Analysis System
SJR	San Joaquin River
SPL	sound pressure level
VAMP	Vernalis Adaptive Management Program

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2010 Effectiveness of a Non-Physical Fish Barrier at the Divergence of the Old and San Joaquin Rivers (CA)

I. Introduction

In 2010, the U.S. Department of the Interior/Bureau of Reclamation (Reclamation) worked in coordination with Fish Guidance Systems (Southampton, England), Ovivo USA, LLC (Salt Lake City, UT, formerly EIMCO Water Technologies), Hydroacoustic Technology Inc. (Seattle, WA), the San Joaquin River Group Authority (Davis, CA) and the California Department of Water Resources (Sacramento, CA) to design, implement, and monitor a non-physical barrier called the Bio-Acoustic Fish Fence (BAFF). The BAFF was deployed upstream of the divergence (Divergence) of the San Joaquin River (SJR) and Old River (OR). The BAFF intended to deter anadromous salmonid juveniles from entering Old River. The BAFF is comprised of three components: sound, bubble curtain, and hi-intensity light-emitting diode (LED) Modulated Intense Lights (formerly known as stroboscopic lights in previous technological memoranda). Patent issues require us to use the term Modulated Intense Lights (MILs) but the lights used in 2010 are the exact same design as 2009. The BAFF was deployed in the San Joaquin River immediately upstream of the Old River and it will be referred to in this document as the Old River Barrier (ORB) or BAFF. This is the second installment of a BAFF at the Divergence. In 2009, we installed a BAFF which used the same deterrence components but was straight, shorter than the 2010 configuration and had a slightly smaller incident angle (6^o) at the origin.

Reclamation assisted in planning the deployment of the ORB. We provided technical assistance in delivering sound, bubble, and MIL stimuli to anadromous salmonids at the same intensity as our laboratory model in the Water Resources Research Laboratory (Denver, CO). Our laboratory model showed statistically significant deterrence of Chinook juveniles caused by a BAFF (Bowen et al., 2008) similar to that we installed at the Divergence.

The monitoring of the ORB was conducted by Reclamation with the cooperation of the Vernalis Adaptive Management Program (VAMP) team. The VAMP team used acoustic telemetry to assess survival rate in several routes through the Sacramento-San Joaquin Rivers Delta (San Joaquin River Group Authority, 2010).

The primary release point for the 2010 VAMP experiments was Durham Ferry, several miles upstream of the San Joaquin River-Old River Divergence. The Chinook smolts with acoustic transmitters that were released there and survived to the Divergence were detected by an array of eight hydrophones deployed in the vicinity of the Divergence. These detections provided measures of Deterrence Efficiency and Protection Efficiency as the Chinook smolts passed through the area of the ORB. Fish that were deterred by the ORB and remained in the San Joaquin River are thought to be more likely to survive than fish that enter Old River. Some data that suggest survival is higher in the San Joaquin River path can be found in Holbrook et al., 2009. Chinook smolts that pass through the barrier undeterred are more likely to be entrained into the Central Valley Project and State Water Project intakes that are located on Old River.

In addition to acoustic telemetry, we used one other evaluation methodology. A Dual-frequency Identification Sonar (DIDSON) camera was deployed immediately upstream of the barrier. The DIDSON recorded images throughout the period after each VAMP release. These DIDSON recordings were used primarily to observe the behavior of fishes in the vicinity of the barrier and are not quantified in this technical memorandum.

II. Methods

The BAFF (Fish Guidance Systems, Southampton, England) installation was completed by April 16, 2010. After installation of the BAFF, we installed an HTI (Hydroacoustic Technology, Inc. (http://www.htisonar.com/index.htm)) 8-hydrophone, 2-Dimensional (2D) acoustic telemetry tracking system. Next, we installed the DIDSON camera. All installations were complete before the first VAMP Chinook smolt release took place 4/27/10, 14:02 hr. With this equipment we were able to monitor the seven experimental releases of telemetered Chinook smolts by the VAMP team in real-time at the Divergence.

The BAFF fish barrier combines a number of stimuli and operating principles to maximize fish guidance into a designated channel or collection point. These include customized sound signals, directional MILs and an air bubble curtain (Figure 1). In our model studies at the Water Resources Research Laboratory (Denver, CO), the setup was like that in Figure 1.

The sound, light, and bubble methodologies were selected to confine the effective range of the stimuli to provide precise directional control over fish movements. The deployment and various barrier elements and their interactions are described below.

A. Non-Physical Barrier Description

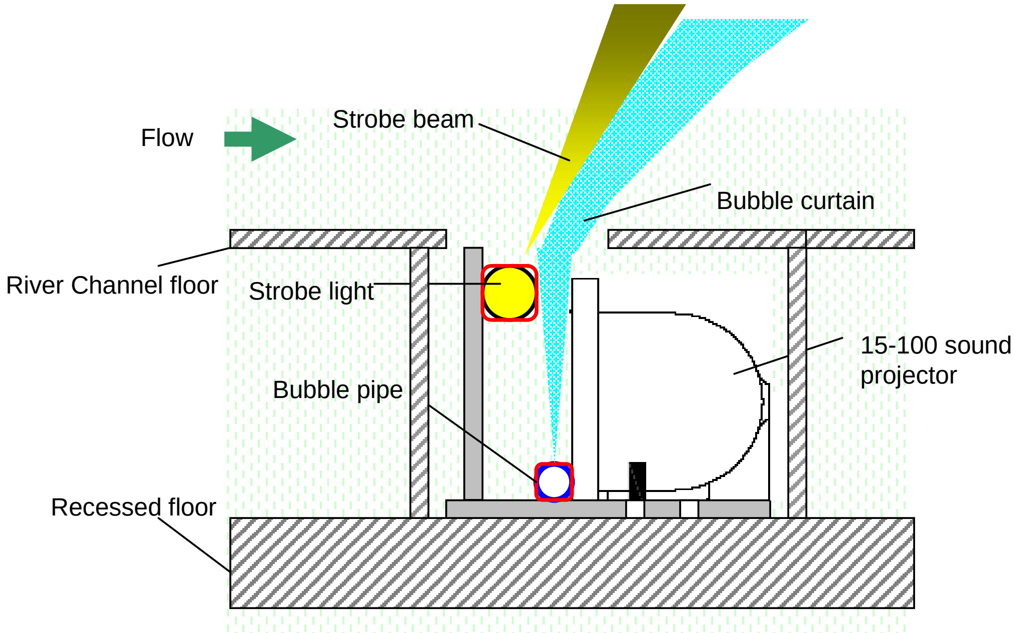

Figure .1 – Bio-Acoustic Fish Fence (BAFF) system set-up.

B. Non-Physical Barrier Deployment

In 2010, the ORB was 136 meters long, comprised of 17 separate 8-meter sections (Figure 2). The barrier frame included 68 sound projectors, 136 MILs, and perforated pipe. Each of the 8-meter sections had adjustable height pivots that provided the flexibility to lower or raise each section to follow the river bed contour. The barrier frame was supported by two piles in the river channel. Additionally, concrete piers were placed to support the frame above the river bed in several locations to make sure the system did move out of alignment and allowed for vertical adjustment of the barrier relative to the river bed or water surface.

The attached drawing, Figure 2, is from Ovivo USA (formerly EIMCO Water Technologies) and shows the plan view layout of the 2010 “hockey stick” configuration. Frames 1-13 are in-line, frames 14, 15, and 16 are each rotated 10° clockwise from the preceding frame, and 17 is in-line with 16.

Each frame had 4 sound projectors, 8 MILs and bubble piping (Figure 3). And the bubble pipe was laid along the frame immediately below and upstream of the sound projectors (Figure 4).

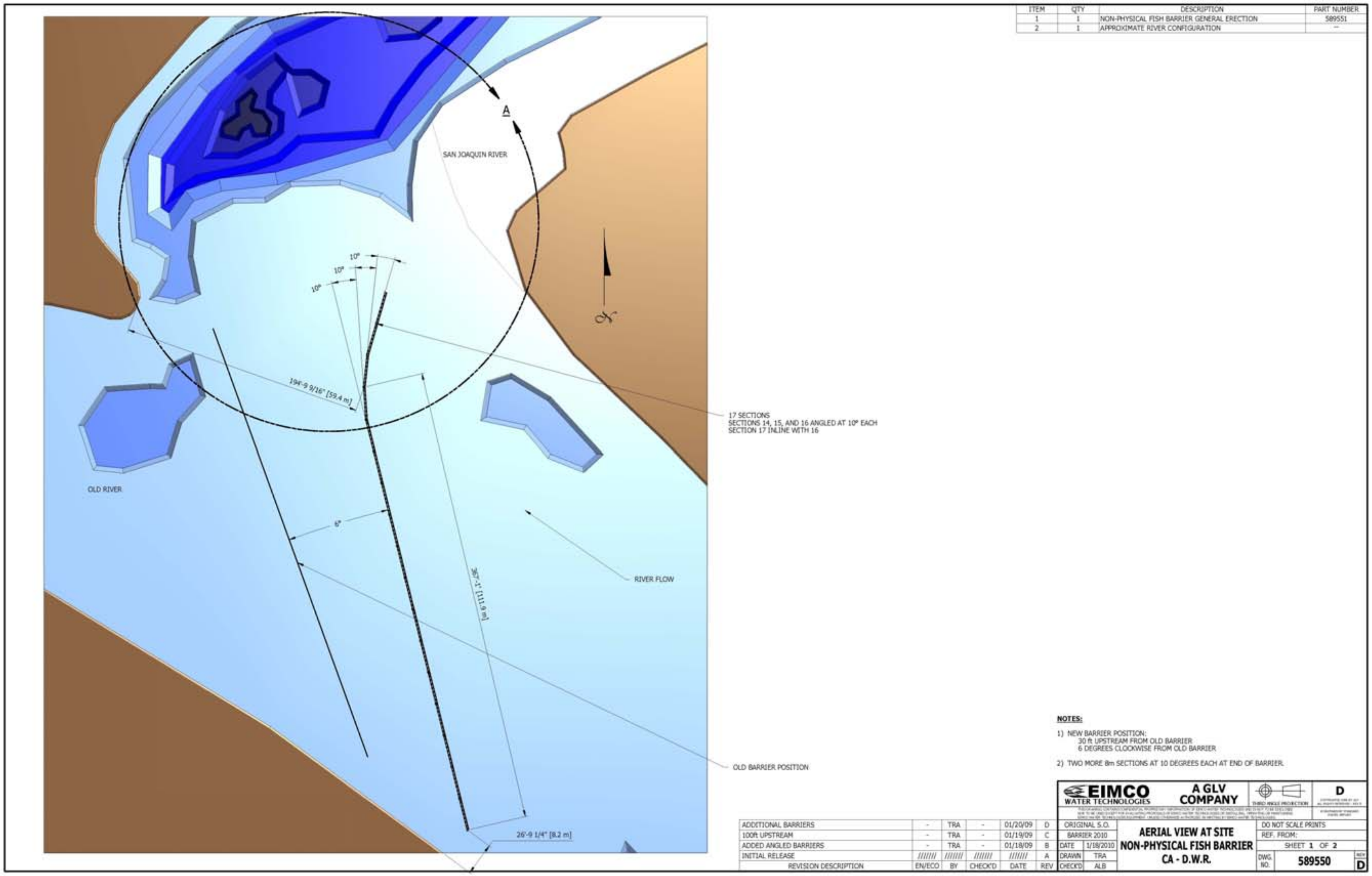

Figure 2. – Schematic layout of the 2010 BAFF at the Divergence of the San Joaquin and Old Rivers (CA). The bold black line indicates the 2010 alignment. The lighter black line downstream of the 2010 alignment indicates the 2009 alignment.

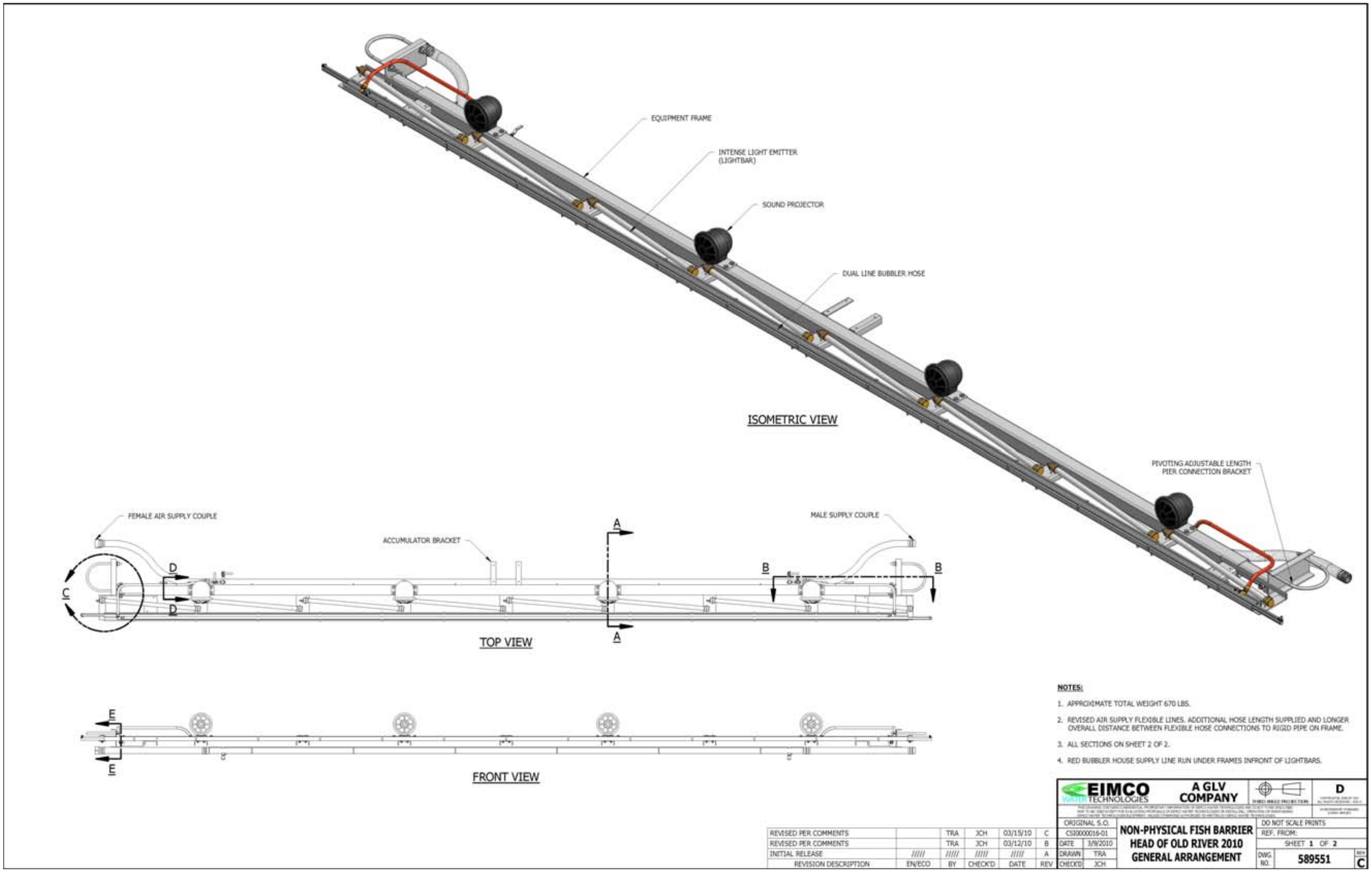

Figure 3. – Non-physical barrier design in the San Joaquin River just upstream of the Old River Divergence. The truss-style frame was lifted by pilings and cement piers 0.45 m off the bottom for the entire length of the barrier.

C. The Acoustic Stimulus

Fish Guidance Systems (FGS) investigated the sensitivities of different fish species and found the most effective acoustic deterrents for multiple species applications fall within the sound frequency range of 5 to 600 Hz. The combined fish barrier generated frequencies within this range at source levels with a maximum measurement for all measurement locations of Root Mean Square (RMS) of Sound Pressure (Pa) of 45.6 (Appendix A). This is equivalent to 153 dB re 1 µPa @ 1m. The signals were delivered by electromechanical transducers, or 'sound projectors'. For the ORB installation, FGS Model 15-100 MkII sound projectors were used, allowing fine control of sound levels within the experimental arena. The sounds were generated by an FGS Model 1-08 Signal Control Unit which fed an FGS Model 400 (400 watt) Power Amplifier, which was linked by cable to the sound projectors.

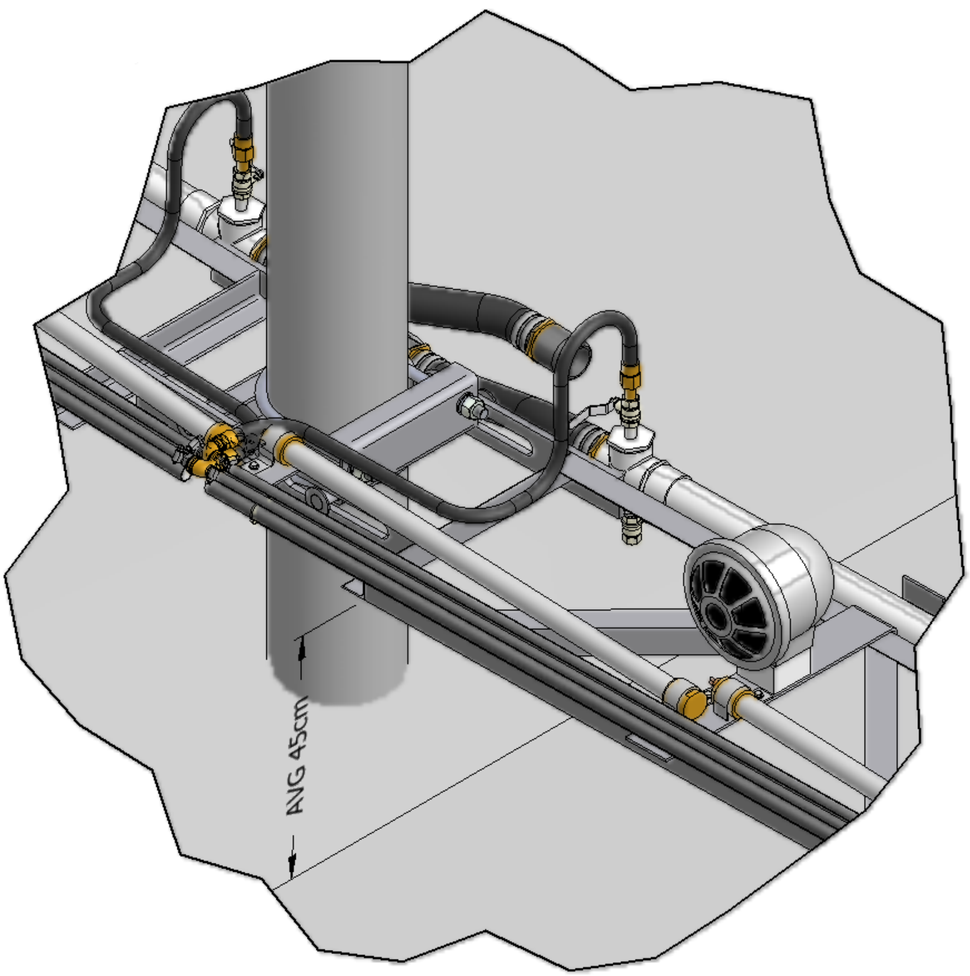

Figure 4. – In this detailed drawing of the truss-style frame, with the BAFF components visible, the distance from the frame to the substrate is indicated as 45 cm. This was the space maintained between the BAFF components and the substrate along the entire length of the BAFF.

D. The Bubble Curtain

The primary function of the bubble curtain was to contain the sound generated by the sound projectors. Using a unique principle patented by FGS, the sound was encapsulated within the bubble curtain, allowing a precise linear wall of sound to be developed. The bubble curtain was generated by passing compressed air (~0.2 bar pressure) into a perforated rubber pipe running along the base of the barrier. Air flow rate was typically around 2.0 liters per second per 1 meter length of barrier. The alignment of the bubble curtain determined the guidance line of fish, enabling them to be directed toward the San Joaquin River. The trapping of the sound signal within the air curtain prevented saturation of the experimental area with sound. This is represented visually in 5.

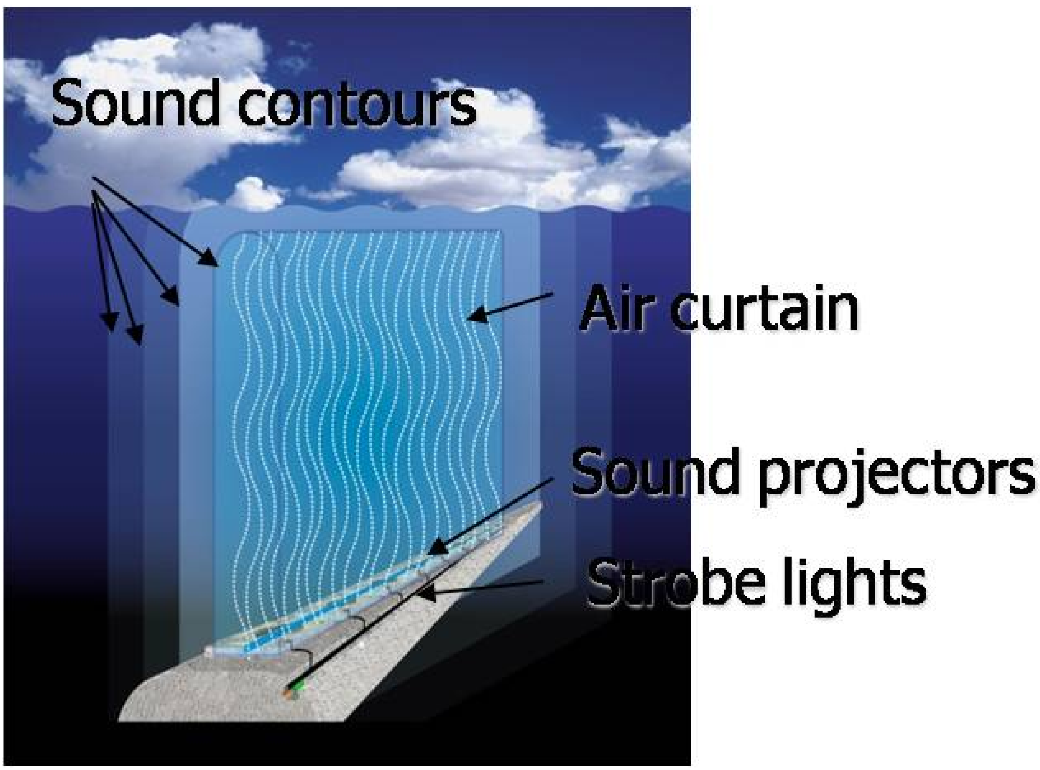

Figure 5. – Conceptual visualization of the Bio-Acoustic Fish Fence using sound, air, and MIL components to deter fish from passing through the barrier.

E. Modulated Intense Lights (MILs)

Fish Guidance Systems Linear MIL Arrays were used to generate the visual stimulus. The MILs are LED powered devices that created white light, flashing off and on, in a vertically orientated beam of 22^{o} beam width. The light arrays were used in the barrier and were aligned such that the beam projects onto the rising bubble curtain. This served to reflect the beam and improved visibility from the direction of approaching fish. The narrow vertical beam angle minimized light saturation within the experimental area. During the day, the MIL's illuminance of the area had fallen to ambient or below at five m from the BAFF (Appendix C). At night, we are not able to say definitively, but it appears the MIL's illuminance of the area had fallen to ambient at 10 m from the BAFF. The MIL system was driven by a low voltage source (<25 V dc) at a flash rate of 360 per minute.

F. Sound Measurements

Measurements of sound emitted by the barrier were measured at 0.61 m from the substrate, in water depths of 2.5 to 3.1 m, and are shown in Appendix A (Frizell and Svoboda, 2010). Sound measurements were taken adjacent to Pile 2 (Figure 6, near Hydrophone 2), at distances of 1, 3, and 5m upstream and 1,3,5, and 10m downstream, orthogonal to the barrier. Waypoints are shown and were recorded at the water surface using a hand-held GPS unit (Figure A1).

Sound pressure levels (SPLs) were measured using a RESON spherical hydrophone model TC4033-1 and was powered through a RESON model EC6081, VP2000 Voltage preamplifier. After filtering (find specifications in Frizell and Svoboda, 2010), root mean squares of sound pressure were reported (Pa) in Appendix A. All instruments were calibrated to international standards.

G. Illumination Measurements

The light was measured with an Ideal Light Technologies Model ILT1700 Research Radiometer. Illumination was measured using the integration feature which sums the incoming light over a specified period. A 60 second time period was used, giving a reading in lumens/.0929m^2 (lumens/sqft) for 60 seconds which can then easily be converted to lux/s. A series of measurements was made, collecting illumination data over a 60 second period for ambient in-air conditions and then underwater at similar locations to the fixed sound measurements. In addition to collecting these measurements with the BAFF Off and On, they were also collected in daylight and at night. Appendix C shows the basic data collected over the period of several days. Unfortunately, near the end of our measurements our meter failed and we were unable to get illuminance with the BAFF Off at night.

H. Acoustic Telemetry Tracking

The ORB was deployed in the San Joaquin River immediately upstream of the Divergence of Old River. To monitor the acoustic tags implanted in the juvenile Chinook salmon, we deployed 8 hydrophones (Figure 6) to provide for 2D tracking in the vicinity of the ORB. Each hydrophone was connected by cable to the HTI Model 290 8-port receiver.

The acoustic tag tracking system consisted of acoustic tags implanted in fish, hydrophones deployed underwater, and an on-shore receiver and data storage computer. Each acoustic tag transmits an underwater sound signal or acoustic "ping" that sends identification information about the tagged fish to hydrophones. The hydrophones were deployed at known locations within the array to maximize spacing of the hydrophones in two (or three) dimensions. For three dimensional tracking, tags must be received on at least four hydrophones; for two dimensional tracking, tags must be received on at least three hydrophones.

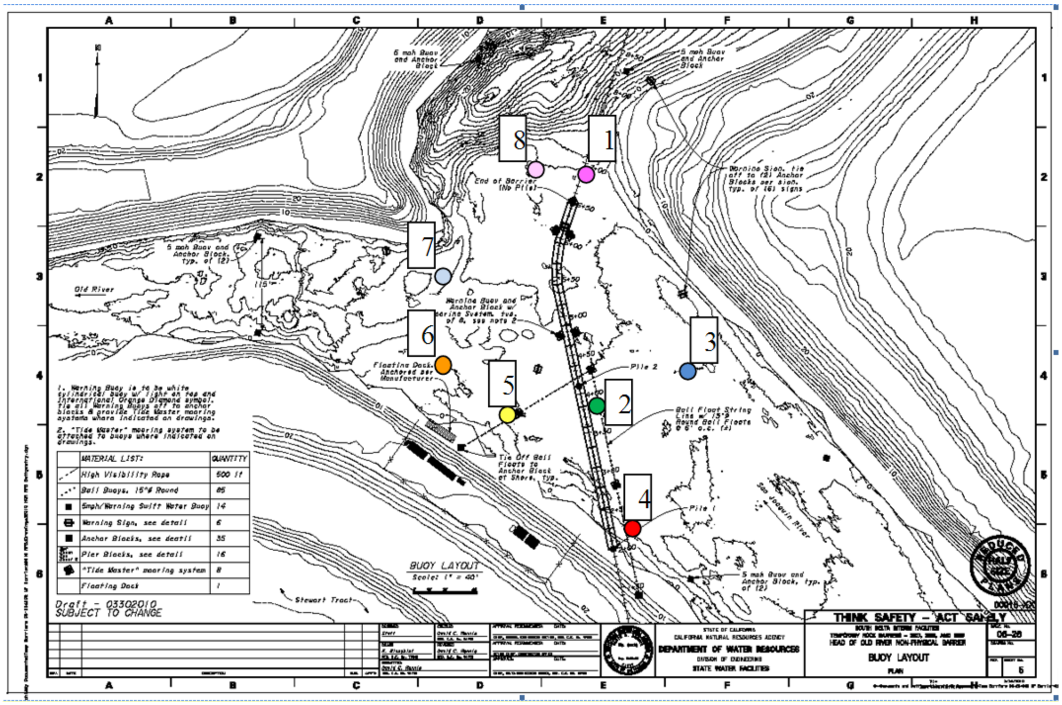

Figure 6. – Divergence of Old River and San Joaquin River, CA. The curved black line indicates the BAFF location. The colored circles exhibit the locations of HTI hydrophones and inside the boxes are their corresponding numbers.

By comparing the time of arrival of the sound signal at multiple hydrophones, the two dimensional (or if the hydrophones are arranged appropriately, the three dimensional) position of the tagged fish can be calculated. The algorithm used to determine the three dimensional tag position from the measured time delays minimizes Equation 1:

Equation1:

$$\sum_{\substack{i,j=1\\ i\neq j}}^{4}\left[(t_i - t_j) - \frac{1}{c}\sqrt{(h_{ix}-F_x)^2+(h_{iy}-F_y)^2+(h_{iz}-F_z)^2} - \sqrt{(h_{jx}-F_x)^2+(h_{jy}-F_y)^2+h_j z-F_z)^2}\right]^2$$

where:

t = arrival time of a tag signal on a given hydrophone,
c = speed of sound in water,
h = hydrophone position in each dimension, and
F = tag position in each dimension.

Because of the depth in this section of the San Joaquin River, we were not able to acquire 3D data. In order to use the system for two dimensional tracking, the above equation is simplified to include only the X and Y dimensions using time delays from only 3 hydrophones. The HTI Acoustic Tag data collection and analysis software program allowed us to select two dimensional tag tracking.

Individual tag positions were then assembled in chronological order to form a two dimensional (2D) trace representing the movement of the fish as it passed through the array. This process was done from stored arrival time data (from Raw Acoustic Tag files), and in real time through the acoustic tracking system. The estimated positioning resolution of the acoustic detection system, within the outline of the eight hydrophones (indicated on Figure 6), was approximately 1 m (S. Johnston, personal communication).

The 8-hydrophone array was adjusted until optimal 2D coverage was achieved. Our goal was to provide the best achievable coverage of the experimental area while maximizing our ability to determine the fate of each fish: 1) Old River, 2) San Joaquin River, 3) predation, 4) unknown or 5) never arrived at the ORB area.

I. DIDSON Observations

We deployed a DIDSON camera immediately upstream of the ORB (Figure 7). The camera was placed in the water near the shore and origin point of the BAFF. The camera head was on a rotator and was 75 cm upstream of the ORB. The detection cone was aimed parallel to the BAFF for recording. The images of the DIDSON were recorded for 3 hr prior to and after the BAFF was switched On or Off.

J. Vernalis Adaptive Management Program's Experimental Releases

The VAMP team inserted HTI acoustic transmitters in 508 Chinook salmon smolts (target size 100-110 mm TL) and released them alive. These fish were released in seven groups upstream of the ORB at Durham Ferry. Approximately, one quarter of the total number were released every 6 hours beginning at 1400 hr. Subsequent releases were made at 2000, the next day at 0200, and finally at 0800. The data for all four releases in each 24 hr period are summarized in Table 1.

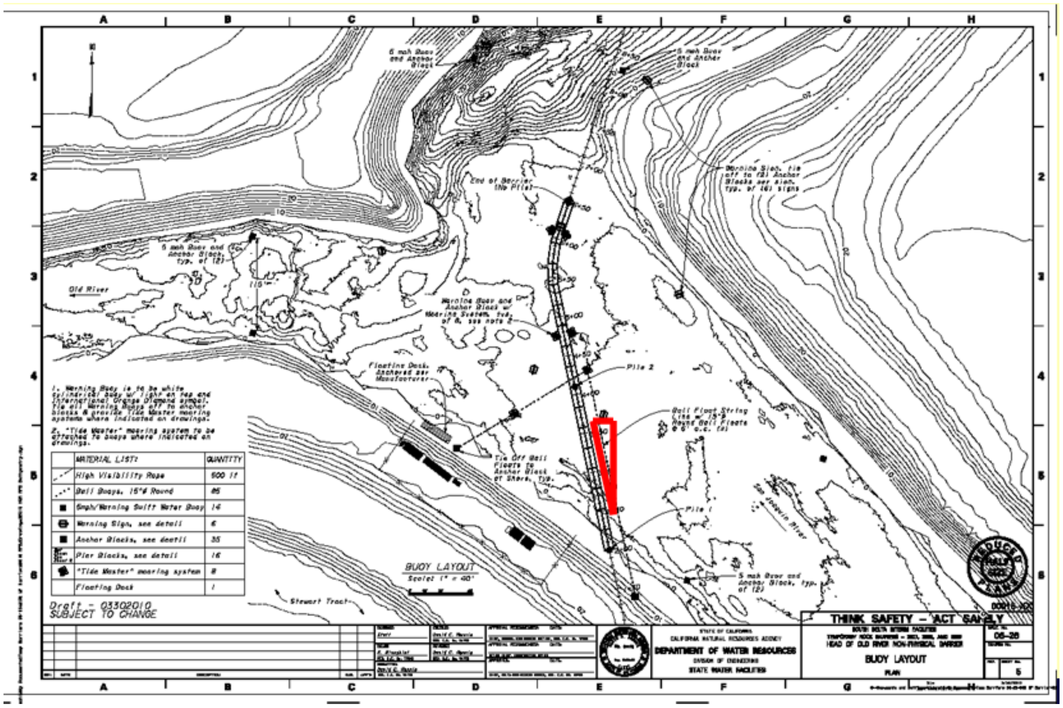

Figure 7. – Schematic representation of the DIDSON camera's deployment in the San Joaquin River. The BAFF is indicated by the three parallel black lines: the central line is the BAFF and the two parallel lines on either side are buoy lines. The DIDSON viewing cone is indicated along the BAFF line in red.

Table 1. – Total Number Liberated and Release Period for Each Experimental Replicate.

Release Number	Date	Number Released
1	4/27-4/28	74
2	4/30-5/02	71
3	5/04-5/05	73
4	5/07-5/08	72
5	5/11-5/12	71
6	5/14-5/15	74
7	5/18-5/19	73

K. Bio-Acoustic Fish Fence (BAFF) Monitoring Experiment

Each of the VAMP releases comprised one replicate for determining Proportion Deterred (D) for the BAFF. We maintained the barrier "On" for a period and the barrier "Off" for a period during each of the seven releases/replicates. If we did not have an On/Off experiment in each release we would have completed N=3 replicates barrier Off and N=4 replicates barrier On. Thus, we greatly increased our power by completing On/Off experiments within each release. We wanted to expose at least 20 of the telemetered Chinook smolts to the barrier in operation and at least 20 should not experience the barrier. We estimated the minimum number of fish we wished to have passed the BAFF to evaluate deterrence efficiency at 20. We estimated the loss that would occur due to predation was 30% or 6 fish out of 20. So, we used a Count Number of 26. When the telemetered smolts were released we began real-time monitoring for a replicate. As each fish passed by we observed it by determining which hydrophones could hear it. As the fish moved through the area, first the most upstream hydrophones could hear the tag. Then, as the fish moved out of the area, only the most downstream hydrophones could hear the tag. When no hydrophones could any longer hear the tag, the tag was added to the count. When the count reach the Count Number the BAFF was switched to the opposite state.

We also wanted an approximately equal amount of time with barrier On and the barrier Off over the course of the seven replicates. In addition, we wished to have the barrier On and the barrier Off over a range of light and tidal conditions. Two full tidal cycles are competed every 25 hours. Twenty-five hours also covers the complete range of light conditions.

Using these parameters the final completed schedule we executed can be found in Table 2 along with the transit time of the first fish arriving from a release and the last fish arriving from a release.

We established the pattern of starting the experiment Barrier Off (Coded 1) or Barrier On (Coded 2) with random draws of a sequence of two. The random draws were: 2-1, 2-1, 2-1, 1. So then, the seven replicates began in this order: 1) Barrier On, 2) Barrier Off, 3) Barrier On, 4) Barrier Off, 5) Barrier On, 6) Barrier Off, and 7) Barrier Off.

L. Operational Problems with the Old River Barrier

We began operations according to the schedule in Table 2. We encountered a number of problems with the operation of the ORB in 2010 (Table 3).

Table 2. – Bio-Acoustic Fish Fence (BAFF) Operation Schedule with Transit Times from Durham Ferry to the ORB for the First and Last Tag of Each Release (Release Number:(Tag nearest time to BAFF – Release Date and Time)). All dates in 2010. ND = No Data. When the last arriving fish does not arrive before the next release begins, that fish's arrival is found in chronological order with no entry in the Barrier State column.

Release	Date	Time	Barrier State	Duration to	
				1st Tag	Last Tag
1	4/27	14:00 hr	On	1:0 d, 09:21 hr	ND
1	4/28	08:58 hr	Off	ND	ND
1	4/29	09:58 hr	On	ND	ND
1	4/29	10:58 hr	Off	ND	ND
2	4/30	14:00 hr	Off	2: 0 d, 9:02 hr	ND
2	5/1	06:16 hr	On	ND	ND
2	5/2	07:16 hr	Off	ND	2: 1 d, 6:11 hr
1	5/2	02:05 hr		ND	3:3 d, 17:53 hr
2	5/3	08:16 hr	ON	ND	ND
3	5/4	09:16 hr	Off	ND	ND
3	5/4	14:00 hr	On	3: 0 d, 7:59	ND
3	5/5	12:30 hr	Off	ND	ND
3	5/6	13:30 hr	On	ND	ND
4	5/7	14:00 hr	Off	4:0 d, 8:15 hr	ND
4	5/8	06:27 hr	On	ND	ND
4	5/9	07:27 hr	Off	ND	4:0 d, 22:20 hr
4	5/10	08:27 hr	On	ND	ND
5	5/11	09:27 hr	Off	ND	ND
5	5/11	14:00 hr	On	5:0 d, 8:32 hr	ND
5	5/12	06:54 hr	Off	ND	5:0 d, 21:21 hr
5	5/13	07:54 hr	On	ND	ND
3	5/13	23:39 hr		ND	3: 9 d, 9:37 hr
6	5/14	08:54 hr	Off	ND	ND
6	5/14	14:00 hr	Off	6: 0 d, 8:37 hr	ND
6	5/15	09:27 hr	On	ND	6:0 d, 21:05 hr
6	5/16	10:27 hr	On	ND	ND
6	5/17	11:27 hr	On	ND	ND
7	5/18	12:27 hr	Off	ND	ND
7	5/18	14:00 hr	Off	7:0 d, 9:56 hr	ND
7	5/19	08:04 hr	On	ND	7:0 d, 22:54 hr
7	5/20	09:04 hr	Off	ND	ND
7	5/21	10:04 hr	On	ND	ND
7	5/22	11:04 hr	Off	ND	ND
7	5/23	12:04 hr	On	ND	ND
7	5/24	13:04 hr	Off	ND	ND
7	5/25	14:04 hr	On	ND	ND
7	-	ALL DAYS	On	ND	ND

Table 3. – Changes and Repairs Made to the Old River Barrier in 2010.

Date	Location	Work Performed
5/3/2010	Frame 6	Replace bubbler hose
5/6/2010	All Frames	Increased intensity of power supplied to sound projectors
5/7/2010	Frames 4 and 13	Purged valves to regain consistent bubble curtain
5/13/2010	Frame 6	Purged valves to regain consistent bubble curtain
5/19/2010	Frame 6	Purged valves to regain consistent bubble curtain
5/26/2010	Frame 6	Purged valves to regain consistent bubble curtain
6/1/2010	Frame 6	Purged valves to regain consistent bubble curtain
6/7/2010	Frame 3	Replace one high intensity LED MIL

We felt the BAFF was in its best operational condition during experimental Release 7. Due to the many problems experienced, we did a dive inspection immediately before Release 7.

M. Non-Physical Barrier Efficiency Calculations

Together, the VAMP team and Reclamation installed a 8-hydrophone array (Figure 6) at the Divergence, two fixed stations in the Old River downstream of the Divergence, and two fixed stations in the San Joaquin River downstream of the Divergence that detected telemetered Chinook smolts passing through the area. We used the 8-hydrophone array to produce 2D traces and to determine the response to the BAFF and the fate of fish.

We determined the response to the ORB by inspecting the 2D trace when the tag approached the BAFF. This was coded as response and had the possible values: 1) undeterred by the BAFF, 2) deterred by the BAFF, 3) never experienced the BAFF, 4) unknown, and 5) discard. A fish was discarded if it was in the hydrophone array at the time the barrier was switched On of Off.
After we determined response to the BAFF, we analyzed the fate of fish. We inspected the 2D trace and compared that to Old River fixed station data to confirm or improve our understanding of the fate. We also reviewed, for every tag, the set of echoes received for each hydrophone. The possible fates of a tag determined in this way were 1) Old River, 2) San Joaquin River, 3) predation, 4) unknown or 5) never arrived at the ORB area.

N. Deterrence Efficiency

Proportion Deterred may be calculated as

Equation 2:

$$D = E/(E+U)$$

where,

D = Proportion Deterred,
E = number of fish deterred, and
U = number of fish undeterred, and
Deterrence Efficiency is calculated as Proportion Deterred * 100.

The numerator is composed of all fish that were deterred, determined by direct inspection of 2D traces. The denominator is composed of all fish making a decision in the immediate vicinity of the BAFF. The "immediate vicinity" was considered to be inside the maximum reactive distance for juvenile salmon. For this BAFF deployment, it was 5 m or less from the barrier during the day and 10 m or less at night (A. Turnpenny, personal communication and Appendix A and 3). Grand Deterrence Efficiency was calculated as the total number of fish deterred, summing all seven releases, divided by the sum of all fish for which the response could be determined multiplied by 100.

O. Protection Efficiency

We used only acoustic-tagged fish that moved through the area and continued downstream to calculate the Protection Efficiency as

Equation 3:

$$P = S/(S+R)$$

where,

P = Protection Efficiency,
S = number of Chinook smolts passing down into the San Joaquin River, and
R = number of Chinook smolts passing down into the Old River.

The denominator is composed of all fish making a decision and passing into the San Joaquin River or the Old River. Fish that do not pass on through could have been eaten by a predator before encountering the BAFF; so, these fish are not included in the calculation. We determined Protection Efficiency when the BAFF was Off and when the BAFF was On for each release. Grand Protection Efficiency was calculated for barrier Off and barrier On as the total number of fish going down the San Joaquin River, summing all seven releases, divided by the sum of all fish for which the fate could be determined. All fish that were known to have been the victims of predation were excluded from the calculations of Protection Efficiency.

P. Overall Efficiency

For Overall Efficiency, we used all acoustic tags originally implanted in Chinook salmon regardless of whether they were ever determined to be in predators or not. All tags that arrived at the area of the Divergence were used to calculate Overall Efficiency.

Equation 4:

$$O = T/A$$

where,

O = Overall Efficiency,
T = number of tags passing down into the San Joaquin River, and
A = total number of tags arriving in the area of the Divergence (that entered the acoustic telemetry array).

The denominator is composed of all tags, even those eaten by predators, making a decision and passing into the San Joaquin River or the Old River. Tags that do pass on could have been eaten by a predator before encountering the BAFF and carried past the BAFF in the stomach of the predator; so, these fish are included in the calculation. We determined Overall Efficiency when the BAFF was Off and when the BAFF was On for each release. Grand Overall Efficiency was calculated for barrier Off and barrier On as the total number of tags going down the San Joaquin River, summing all seven releases, divided by the sum of all tags for which the fate could be determined. All fish that were known to have been the victims of predation were included in the calculations of Protection Efficiency.

Q. Hypothesis Testing

In 2010, we conducted three hypotheses tests:

1) H_1: Proportion Deterred when the barrier is On is not equal to Proportion Deterred when the barrier is Off.

2) H_2: Protection Efficiency when the barrier is On is not equal to Protection Efficiency when the barrier is Off.

3) H_3: Overall Efficiency when the barrier is On is not equal to Overall Efficiency when the barrier is Off.

After concluding this analysis we conducted three more hypotheses tests:

1) H_4: Proportion Deterred when the barrier is On is not the same in 2009 and 2010.

2) H_5: Protection Efficiency when the barrier is On is not the same in 2009 and 2010.

3) H_6: Overall Efficiency when the barrier is On is not the same in 2009 and 2010.

We tested each of these hypotheses by first evaluating the data for assumptions of Analysis of Variance: 1) independence of observations, 2) homogeneity of variance, and 3) normality. Second, if the data meet these three criteria we conducted a one-way ANOVA: Barrier Off vs. Barrier On or 2009 vs. 2010. Third, if the data do not meet the assumptions of ANOVA we used a non-parametric technique: Kruskal-Wallis. All analyses were conducted with Statistical Analysis System (SAS, Cary, NC).

III. Results

A. Predation Before and Near the Old River Barrier

For each release, we calculated the Proportion Never Appearing at the ORB (Table 4). In addition to fish that never appeared at the ORB area, we also determined the number of fish that were eaten in the ORB area by inspecting every 2D trace for all of the released 508 fish that appeared in the ORB area. The proportion that appeared and for which there was strong evidence of predation is found in Table 4. In Table 4, we also sum the predation before the ORB area and in the ORB area to find the total estimated predation proportion from Durham Ferry passed the Divergence.

In addition to our quantification of predation in the ORB area, we studied the behavior of predators at the site. Our regular observation of the area upstream of the line between Piles 1 and 2 with the DIDSON camera showed interesting behaviors. First, we could identify striped bass with the DIDSON. These predators were 80-140 cm TL and we could tell they were not sturgeon based on their silhouette. The striped bass would swim in looping patterns pursuing patrolling behavior throughout the ORB area. The striped bass would also swim along the non-physical barrier infrastructure. Another important difference between predators and smolts was their swim speed. Generally, we found the predators swim slower than smolts.

Table 4. – Mortality Rate of Chinook Smolts: 1) Between Durham Ferry and the San Joaquin/Old River Divergence, 2) in the Divergence Area, and 3) Sum of Predation (1 and 2) from Durham Ferry Past the Divergence Area.

Release	Number Released	Proportion Never Arrived at ORB	Proportion Consumed in ORB Area	Total Dead Combined Proportion (before and in ORB area)
1	74	0.081	0.257	0.338
2	71	0.028	0.169	0.197
3	73	0.082	0.205	0.287
4	72	0.042	0.194	0.236
5	71	0.042	0.183	0.225
6	74	0.068	0.270	0.338
7	73	0.205	0.370	0.575

The predation rates, before arriving at the ORB ranged from 2.8 to 20.5 percent for each release group of approximately 72 smolts. These predation rates were generally lower than 2009 and led to good numbers of fish available to evaluate the ORB. We operated the BAFF about half the time with the barrier Off and about half the time with the barrier On leading to lower sample sizes in each division. But still, we met our objective of 20 fish for the evaluation of D, P, and O for BAFF On and Off for almost every release.

B. Deterrence Efficiency

We acquired echoes from every tag that appeared at the Old River Barrier. We attempted to construct a 2D trace (Figure 8) for every one of these tags. From inspection of the 2D traces, we observed a number of tags that were clearly deterred (Figure 9). We enumerated the fish that were deterred like smolt 8073. And, we counted those that were undeterred like tag 5437 (Figure 8).

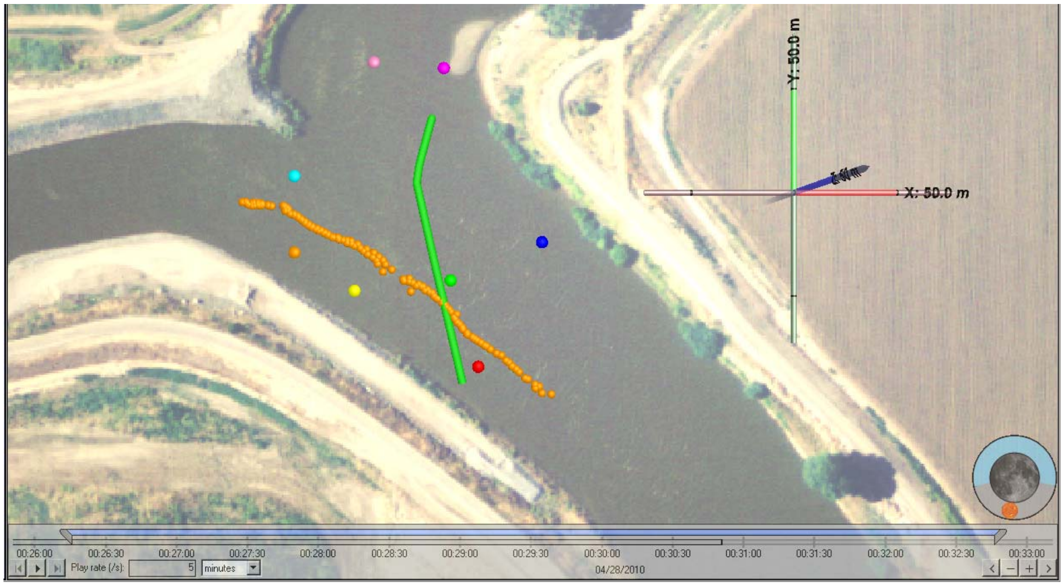

Figure 8. – 2D trace of a Chinook smolt at the San Joaquin/Old River Divergence. The green line indicates the BAFF location and the colored circles indicate the location of the eight hydrophones. This 2D trace is Tag 5437 that crossed the BAFF line while in operation on 4/28/10. This entire track required only 7 min for the Chinook smolt to pass through the area, 13:26 – 13:33 hr.

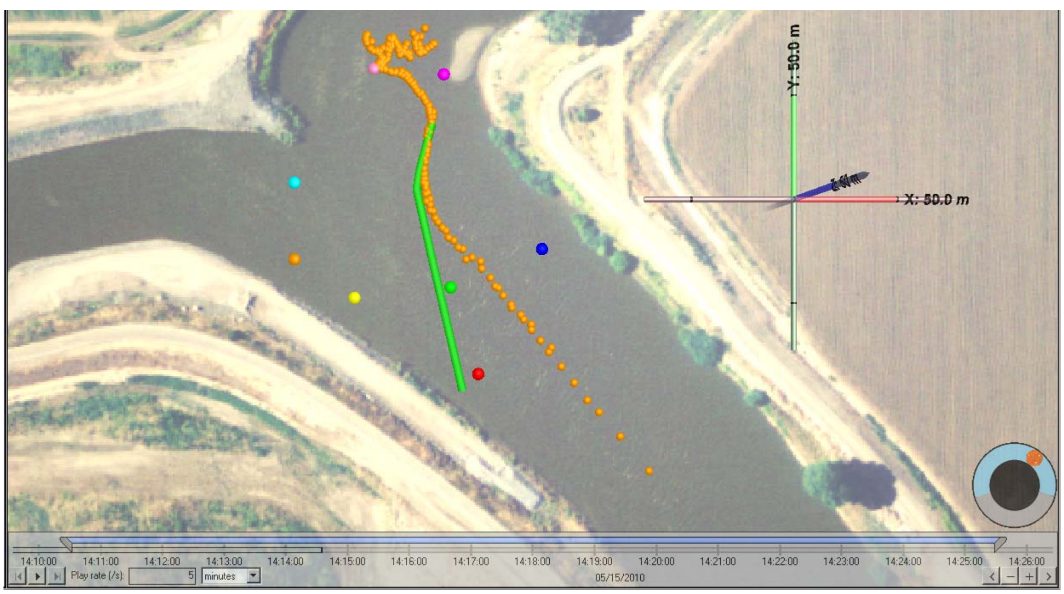

Figure 9. – Tag 8073 approached the barrier in operation on 5/15/09 at 14:00 hr. The tag exhibits a smolt-like trace: downstream quickly and no looping predator behavior. The staggered motion after the smolt exits the hydrophone array is a tracking artifact or the presence of a predator. This smolt was obviously deterred by the BAFF. The green line indicates the BAFF location and the colored circles indicate the location of the eight hydrophones.

In 2010, the grand Deterrence Efficiency when the barrier was On was 23.0 percent (Table 5). When the barrier is Off, the grand Deterrence Efficiency is 0.5 percent (Table 5). There is a highly significant difference between these two sets of observations displayed in Table 5 (Kruskal-Wallis $X^2 = 10.6167$, p = 0.0011). The BAFF significantly deterred Chinook smolts based on statistics. However, the BAFF was not nearly as effective as it was in 2009. In 2009, the grand Deterrence Efficiency with the barrier On was 81.4%. We compared the set of observations of D in 2009 and the set of observations in 2010 and found that 2009 deterrence was significantly higher (Kruskal-Wallis $X^2 = 7.5469$, p = 0.0060).

Table 5. – Proportion Deterred When the Barrier was Off and When it Was On and the Number of Smolts that Were Deterred or Undeterred by the BAFF from Their 2D Trace.

Release	Barrier	Proportion Deterred	Number Deterred	Number Undeterred
1	Off	0.0000	0	33
1	On	0.0769	2	24
2	Off	0.0000	0	28
2	On	0.1316	5	33
3	Off	0.0000	0	28
3	On	0.0263	1	37
4	Off	0.0000	0	23
4	On	0.2308	9	30
5	Off	0.0263	1	37
5	On	0.1250	3	21
6	Off	0.0000	0	19
6	On	0.4118	3	21
7	Off	0.0000	0	19
7	On	0.6667	18	9
Grand D	Off	0.0052	1	191
Grand D	On	0.2301	52	174

C. Protection Efficiency

Holbrook et al. (2009) found that in 2008 only 22-33% of Chinook smolts used the San Joaquin route. In 2009, we found a similar phenomenon: when the barrier was Off, the grand Protection Efficiency is 24.5 percent. In 2010, we found the grand Protection Efficiency with the barrier Off to be 25.9 percent (Table 6). So, for three consecutive years, Chinook smolts passing by the Divergence use the Old River route much more often when no barrier was in operation.

In 2010, the grand Protection Efficiency is 43.1 percent when the barrier was On. Grand Protection Efficiency with the BAFF On is highly statistically greater than when the BAFF is Off (Kruskal-Wallis $X^2 = 8.2835$, p=0.0040). So, in 2010, significantly more smolts survive and continue down the San Joaquin River when the barrier is On compared to when it is Off (see final two rows in Table 6 for values).

In addition, a higher proportion of Chinook smolts survived to continue down the SJR in 2010 than in 2009. In 2009, the grand Protection Efficiency with the barrier On was 30.9 percent (Bowen et al., 2010). We compared the set of observations of P in 2009 and the set of observations of P in 2010 and found that 2009 Protection Efficiency was not statistically higher in 2010 (Kruskal-Wallis $X^2 = 1.8079$, p = 0.1788). But, it is possible that this 12.2% improvement in Protection Efficiency is biologically significant.

Table 6. – Protection Efficiency When Predation is Unknown or Has Not Occurred. SJR = San Joaquin River. OR = Old River.

Release	Barrier	Proportion Efficiency	Number Down SJR	Number Down OR
1	Off	0.3333	9	27
1	On	0.4583	11	13
2	Off	0.2593	7	20
2	On	0.4516	14	17
3	Off	0.1000	2	18
3	On	0.3103	9	20
4	Off	0.3750	9	15
4	On	0.4516	14	17
5	Off	0.2703	10	27
5	On	0.4211	8	11
6	Off	0.2143	6	22
6	On	0.4211	7	9
7	Off	0.1818	2	9
7	On	0.6000	6	4
Grand P	Off	0.2586	45	129
Grand P	On	0.4313	69	91

We found that grand Overall Efficiency is 20.3 percent when the barrier is off (Table 7). The grand Overall Efficiency is 27.6 percent when the barrier is on (Table 7). Overall Efficiency shows less improvement with BAFF off vs. on (7.3 percent) than Protection Efficiency (12.2 percent). A higher proportion of Chinook smolts survived to continue down the SJR in 2010 than in 2009.

Table 7. – Overall Efficiency When Predation Is Unknown or Has Not Occurred. SJR = San Joaquin River. OR = Old River.

Release	Barrier	Overall Efficiency	Number Down SJR	Tags Down SJR or OR
1	Off	0.2368	9	38
1	On	0.3667	11	30
2	Off	0.2121	7	33
2	On	0.3500	14	40
3	Off	0.0714	2	28
3	On	0.2250	9	40
4	Off	0.3333	9	27
4	On	0.2750	11	40
5	Off	0.2051	8	39
5	On	0.3793	11	29
6	Off	0.2069	6	29
6	On	0.1707	7	41
7	Off	0.1429	4	28
7	On	0.2000	6	30
Grand O	Off	0.2027	45	129
Grand O	On	0.2760	69	91

One key to distinguishing the fate of a salmon smolt is to determine if it's been eaten in the vicinity of the BAFF. We observed striped bass behavior using the DIDSON and saw the looping/patrolling behavior that was common in these predators. We also produced a 2D trace for a striped bass tagged in the South Delta (Figure 10). The looping/patrolling behavior, commonly observed with the DIDSON, is easily observed in this 2D track of striped bass 2472. It is obvious that this predator-type track is more similar to Tag 5680 (Figure 11) than to the tracks of Tags 5437 (Figure 8) or 8037 (Figure 9). So, Chinook smolt 5680 was eaten before it approached the BAFF and thus its response is coded "Never Experienced the Barrier." Its fate is coded as "Predation."

D. Overall Efficiency

Because 2010 Overall Efficiency with BAFF On (xx.0%) was so much lower than 2009 Deterrence Efficiency with BAFF On (xx.4%), we questioned if Overall Efficiency with BAFF On.

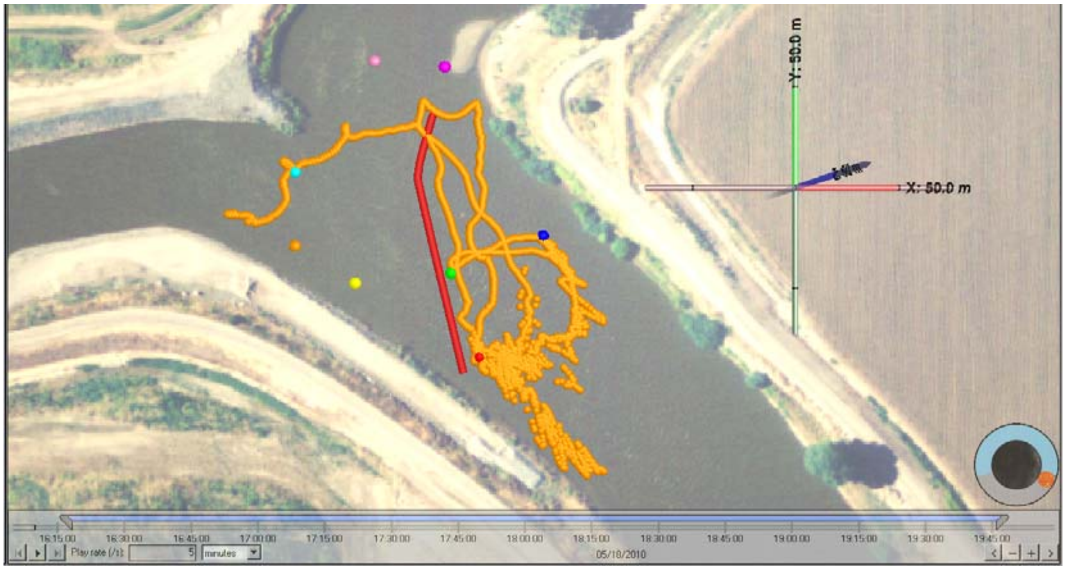

Figure 10. – Track of a striped bass fitted with tag 2472 from May 18, 2010 16:17 hr to 19:34 hr. The red line indicates the location of the BAFF; however the BAFF is not in operation during this tracking. The eight hydrophones are indicated by the eight colored circles.

Figure 11. – Tag 5680 approaches the operating BAFF (Green Line) on 5/8/10 at 06:50 hr. This Chinook salmon was eaten somewhere upstream of the BAFF. The tag exhibits only a little smolt-like behavior near the beginning of this track. The colored circles indicate the location of the eight hydrophones. With stream velocity, the bubble barrier is carried downstream of this green line.

IV. Discussion

In 2010, a statistically higher percentage of Chinook salmon was deterred when the ORB was On (23.0%) than when it was Off (0.5%). Yet, 2010 deterrence with BAFF On, was far lower in 2010 than it was in 2009 with BAFF On (81.4%); and, this difference was significant (Kruskal-Wallis $X^2 = 7.5469$, $p = 0.0060$).

Because 2010 Deterrence Efficiency with BAFF On (23.0%) was so much lower than 2009 Deterrence Efficiency with BAFF On (81.4%), we questioned if Deterrence Efficiency with BAFF On in 2010, while statistically different from 2010 Deterrence Efficiency with BAFF Off, was biologically significant.

We addressed the question of biological significance by an analysis of P. We found that in 2010 when the BAFF was Off the P was 25.9 percent and when the BAFF was On the P was 43.1 percent; these were highly different statistically (Kruskal-Wallis $X^2 = 8.2835$, $p=0.0040$). We concluded that while 2010 BAFF Deterrence Efficiency was much lower than 2009 Deterrence Efficiency, the 2010 deterrence produced significantly better survival, P, than when the BAFF was Off. We argue that significant improvement in survival is the ultimate coin of the success of the BAFF. And, by this measure, the 2010 ORB made a significant contribution.

To summarize, in 2009 there was significantly better deterrence (81.4%) than in 2010 (23.0%). However, high predation kept the Protection Efficiency down in 2009 (30.9). In 2010, there appeared to be lower predation. And, while 2010 deterrence was much lower than in 2009, the 2010 deterrence still made a highly significant contribution to survival (P) down the SJR.

We believe the most probable parsimonious explanation for differences is that in 2010 there were much higher discharges in the experimental period (Table 8) than in 2009.

Table 8. – Discharge (Q) Regime Statistical Moments for 2009 and 2010 During the Experimental Periods. CMS = cubic meters per second. CFS = cubic feet per second.

	2009(cms)	2009(cfs)	2010(cms)	2010(cfs)
Minimum	-50.1	-1771	22.2	785
25th Percentile	-17.5	-619	61.7	2179
Median	32.8	1158	77	2721
75th Percentile	44.6	1575	90.2	3186.5
Maximum	65.1	2300	100.6	3554

These higher discharges could have led to lower Proportions Deterred because of higher velocities through the barrier; the Chinook smolts had less time to avoid the BAFF. This effect is noticeable when we graphed cumulative volume through the experimental area when most smolts were passing through against Proportion Deterred (Figure 12). And, when the discharge decreased and the resulting cumulative volume of water passing the BAFF decreased in Releases 6 and 7 then Proportion Deterred increased. We found further evidence in transit times. We compared Table 2 above to Bowen et al. (2009) Table 1. We found in 12 of 14 comparisons that transit times were faster in 2010 than in 2009 for the fastest and slowest arriving smolts at the ORB.

These higher discharges in 2010 also led to higher velocities through the BAFF (Figure 13). And, in Releases 6 and 7 when the discharges decreased, the average velocity through the BAFF came down. And again, when discharge and velocity decreased Proportion Deterred improved (Figure 12 and 13); the Chinook smolts may have had more time to avoid the BAFF. Of course, we constantly conducted maintenance on the BAFF in 2010. And, we thought that the BAFF was in its best condition during Release 7. So, it is possible that it was BAFF maintenance, velocity reduction, or an interaction of both that led to improved deterrence in Release 7.

We considered another possible factor, temperature, contributing to the improvement in D in Releases 6 and 7. If temperature increased perhaps Proportion Deterred increased as well because smolts, with warmer water temperatures, have increased swimming capacity to avoid the BAFF. However, we determined that temperature was not directly related to Proportion Deterred over this temperature range (Figure 14). During Release 7, when temperature decreased the Proportion Deterred increased. It should be noted that at temperatures warmer than 18^{o}C, temperature may become a more important driver of deterrence than we observed in 2010.

Also, it should be noted that at temperatures warmer than 18^{o}C, temperature may become a more important in the overall efficiency than we observed in 2010 due to increase mobility of warm water predators.

Another phenomenon of interest occurred simultaneously with the discharge decrease in Release 6: the proportion of smolts eaten in the vicinity of the ORB increased (Table 3). And as discharge continued to decrease in Release 7, the proportion of smolts eaten in the vicinity of the ORB increased and there was an increase in the proportion of smolts never arriving at the Divergence. These results suggest that predation from Durham Ferry to the Divergence and in the vicinity of the Divergence may be correlated with velocity. Higher discharges in 2010, and resulting high velocities, in the first five releases could have curtailed predation on Chinook smolts.

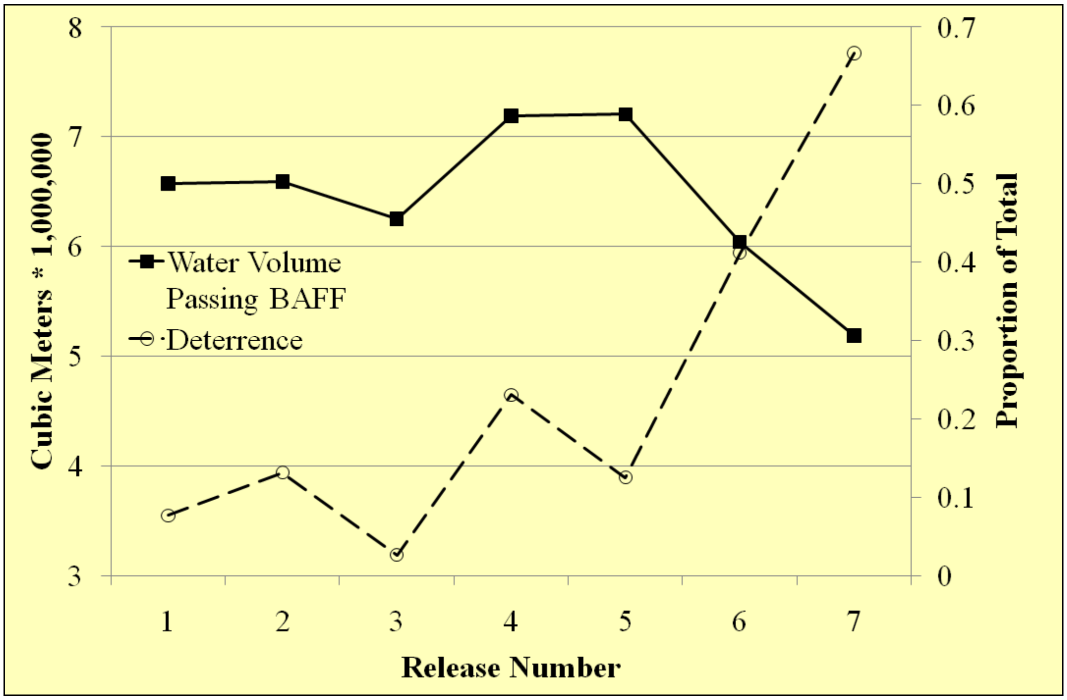

Figure 12. – In 2010, cumulative volume of water passing by the BAFF during the same 24 hr period when an average of 80% of the smolts in each release passed the barrier is graphed versus the proportion deterred for each experimental release group.

It now seems even more likely, given the results of 2010 monitoring, that the high 2009 predation rates we observed were a function of the dry year in the San Joaquin River. Smolts and predators might have been concentrated into a smaller volume of water than in average or wet years. Such a concentration could result in higher encounter rates between predators and smolts leading to an increased predation rate. In addition, lower velocities in drier years may lead to a bioenergetically advantageous situation for large-bodied predators in the open channels near the Divergence.

We recommend that the DWR, determine the hydrologic forecast for the San Joaquin River in March. If a dry year is predicted with the resulting low discharges and low velocities, we recommend, that if the BAFF is installed in 2011, that predator relocation be employed in the ORB area. For example, striped bass and largemouth bass could be moved from the Divergence to San Luis Reservoir. Failure to do so could lead to a similar situation observed in 2009. That is, the BAFF's deterrence may be offset by the heavy predation.

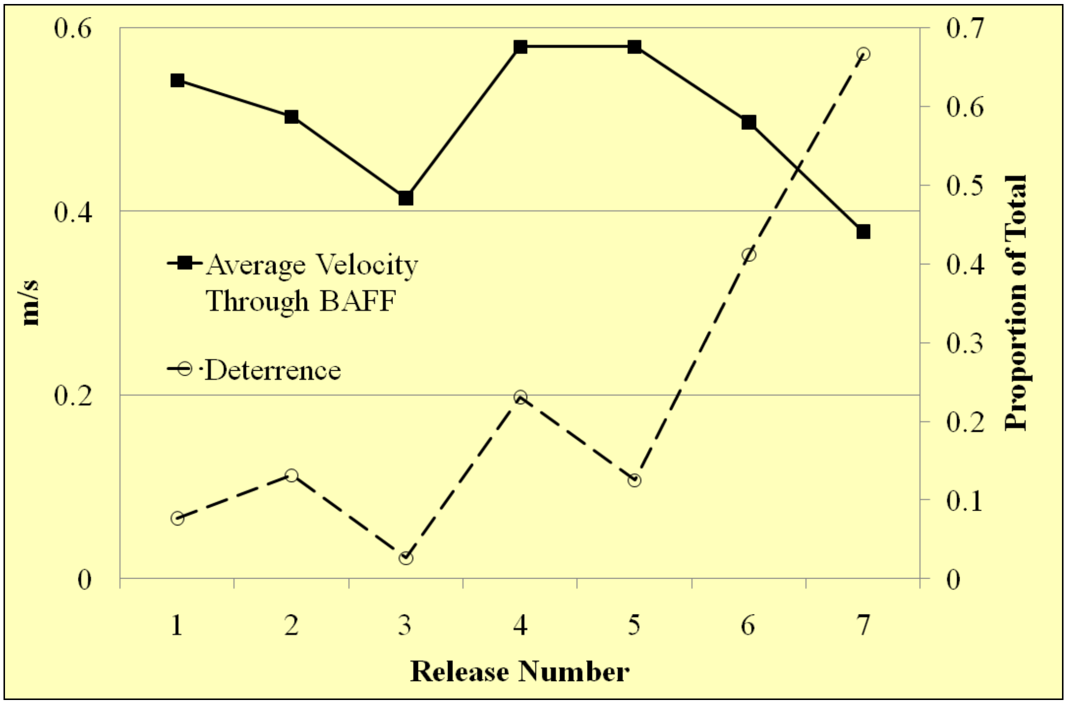

Figure 13. – In 2010, average channel velocity on a cross-section passing through the center of the BAFF during the same 24 hr period when an average of 80% of the telemetered smolts passed the barrier is graphed versus the proportion deterred for each experimental release group.

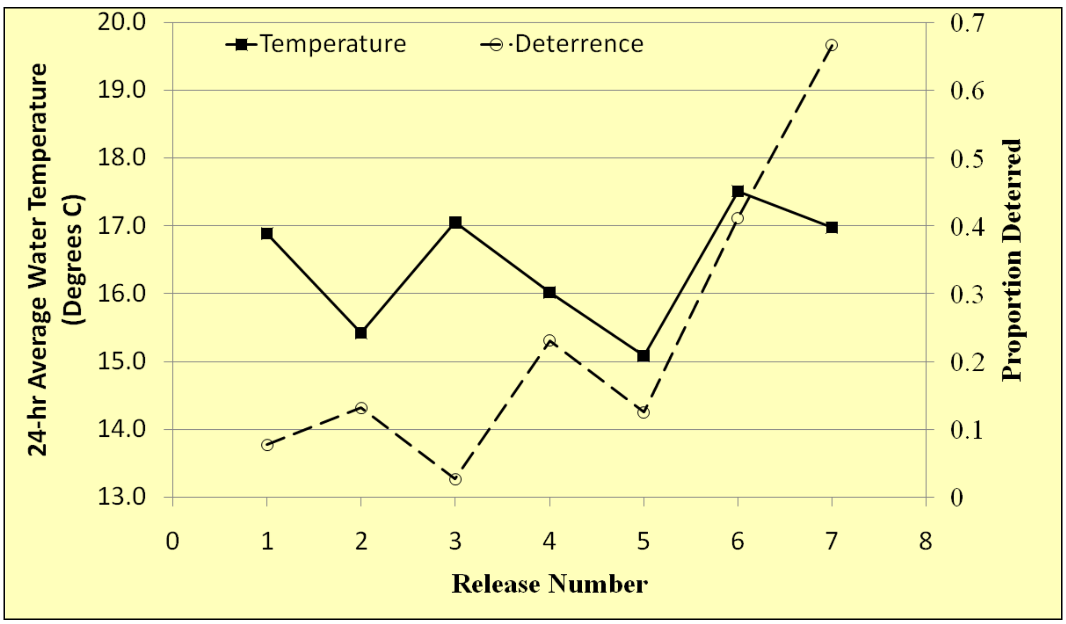

Figure 14. – In 2010, temperature averaged over the same 24 hr period when an average of 80% of the telemetered smolts passed the barrier is graphed versus the proportion deterred for each experimental release group.

We observed differences in Protection Efficiency with the BAFF Off depending on the release (Table 6), tide, and discharge. Protection Efficiency, with BAFF Off, was as low as 0.1000 and as high as 0.3750. We think that at least some of these differences may result from differences in flow fields that change with the tide and subsequent discharge. We provide two examples of flow fields from 2009 monitoring for comparison (Figures 15 and 16).

Overall efficiency displayed a similar pattern as Protection Efficiency. With the BAFF On, depending on the release (Table 7), tide, and discharge, Overall Efficiency was as low as 0.0714 and as high as 0.3793. Again we hypothesized that at least some of these differences may result from differences in flow fields that change with the tide and subsequent discharge.

Why does the barrier work to improve survival for Chinook salmon? It is our opinion that the sound deterred the fish and the bubble curtain contained the sound. The MIL enabled the fish to identify the source of the sound. The fish saw the barrier because of the MILs and they heard the sound as they approached the BAFF. The risk of passing through the barrier to an uncertain future was greater than the risk of swimming away and passing into a different uncertain future but avoiding the source of that sound. In addition in 2010, the BAFF angle was 30^o when in 2009 it was 24^o (Figure 2). The steeper angle and higher velocities may have combined synergistically to give fish less time to evaluate the barrier and avoid it. So, when velocities are high, the fish may pass through it before they can travel the full length of the barrier. Many of these fish will not be successfully deterred by our definition. They may swim some meters (many 2D tracks showed this effect) before passing through the BAFF. That distance improved the probability that the smolt will enter the San Joaquin River. Thus, we observed poor deterrence but significant improvement in protection efficiency, survival, down into the San Joaquin River.

For future installations, we recommended that the BAFF angle be reduced from 30 to 24 degrees. Many fish passed through the barrier because they did not have sufficient time, this was evident from the 2D tracks. And we recommend that the curved elements near the distal end of the 2010 ORB be removed. Many Chinook smolts passed through the BAFF in these curved sections.

Finally, we recommend any new BAFF deployments emphasize that all components of the barrier be fully operational at all times. For example, a self-purging valve system that could keep bubble lines clear of fine sediment could avoid inconsistencies in the BAFF that may allow fish to pass the barrier.

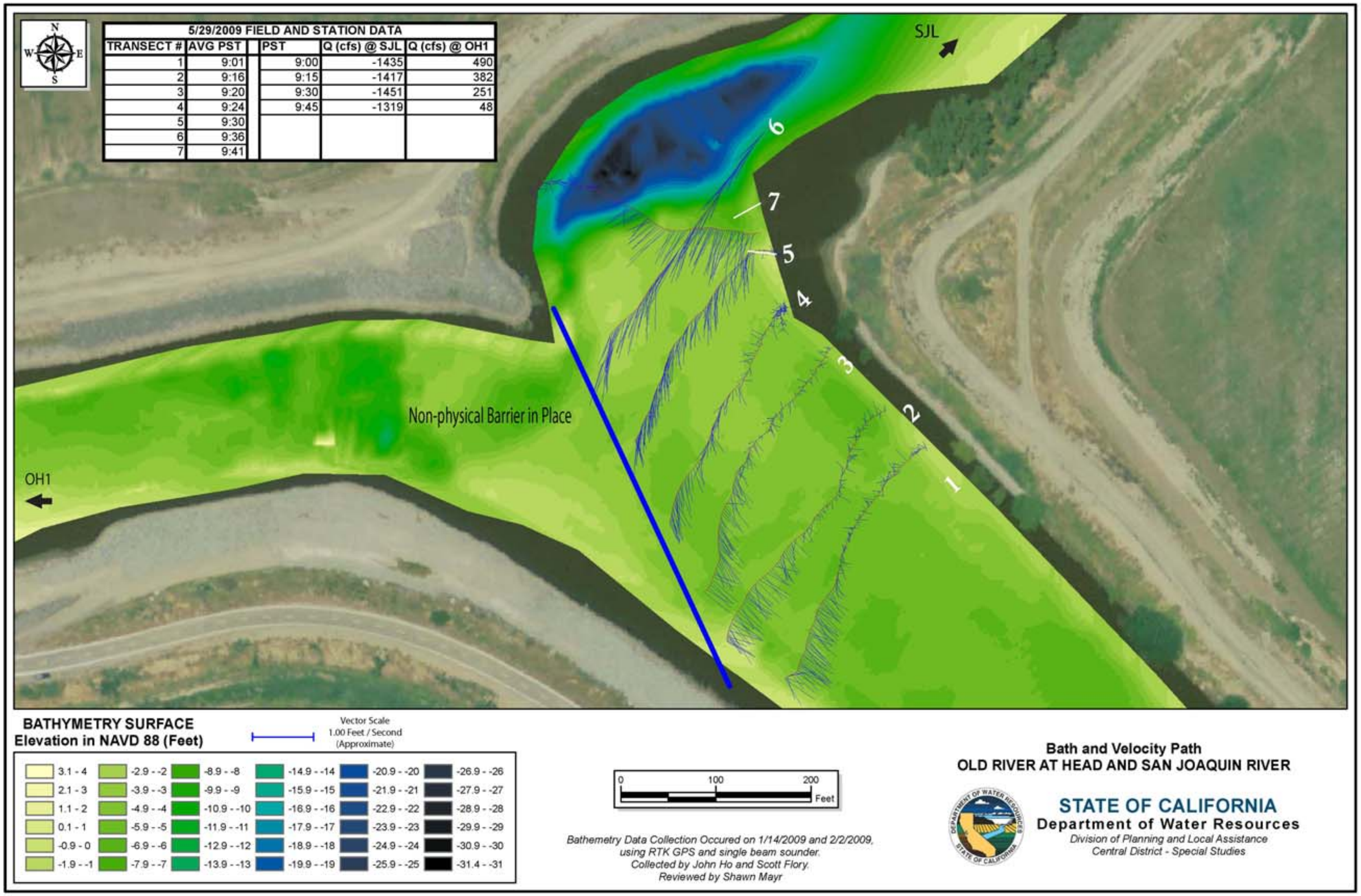

Figure 15. – Velocity field at the Divergence of the San Joaquin River and Old River with a negative discharge at the San Joaquin/Lathop (SJL) gauge. Data and figure supplied by Shawn Mayr, DWR.

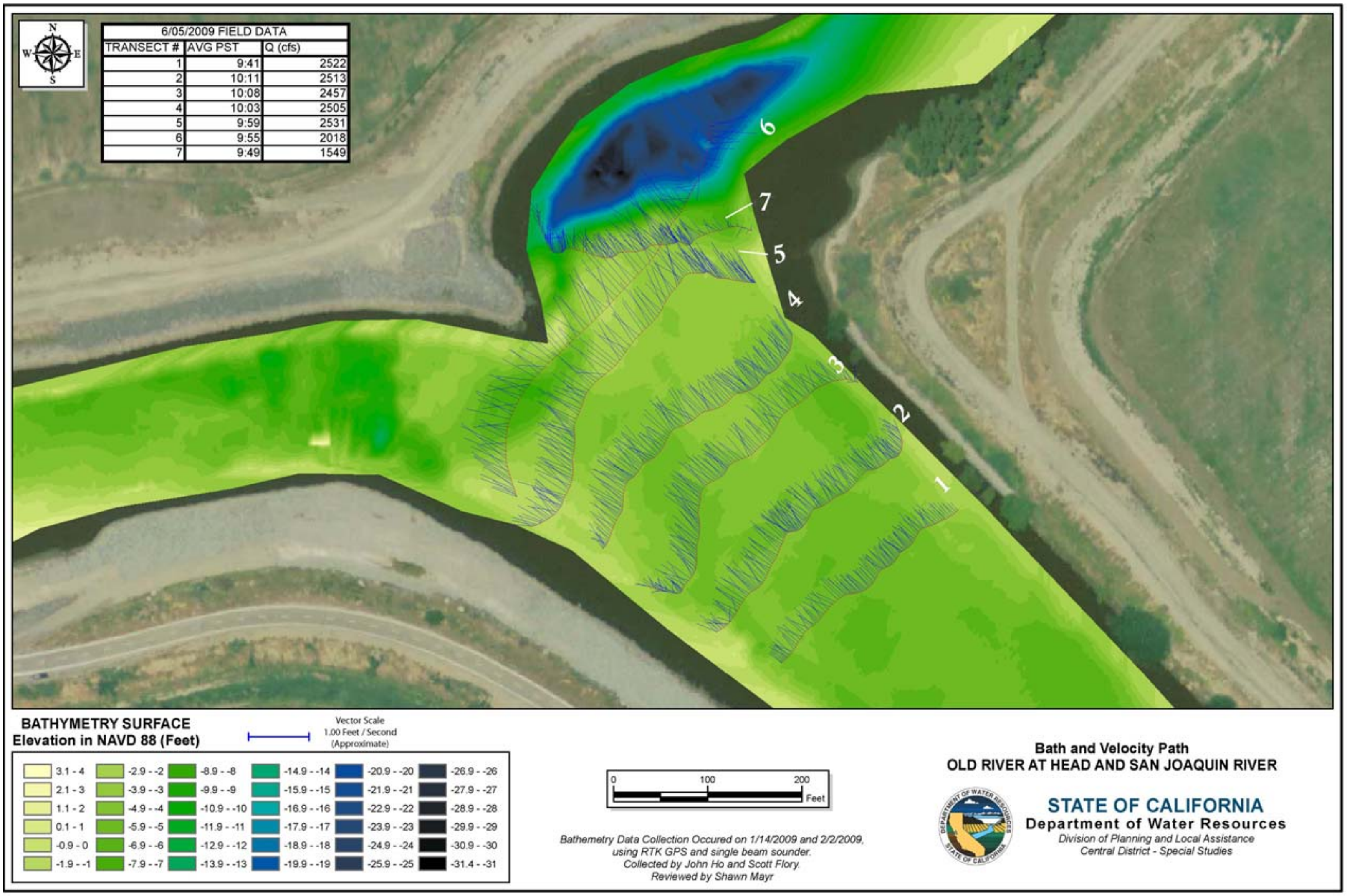

Figure 16. – Velocity field at the Divergence of the San Joaquin River and Old River with a positive discharge. Data and figure supplied by Shawn Mayr, DWR.

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Appendix A – Fixed Sound and Light Measurements at/near Piling 2 (Figure A1)

Hydrophone and light meter located 0.61 m above channel bottom in 2.5 to 3.1 m of water, discharge measurements from Mossdale gage.

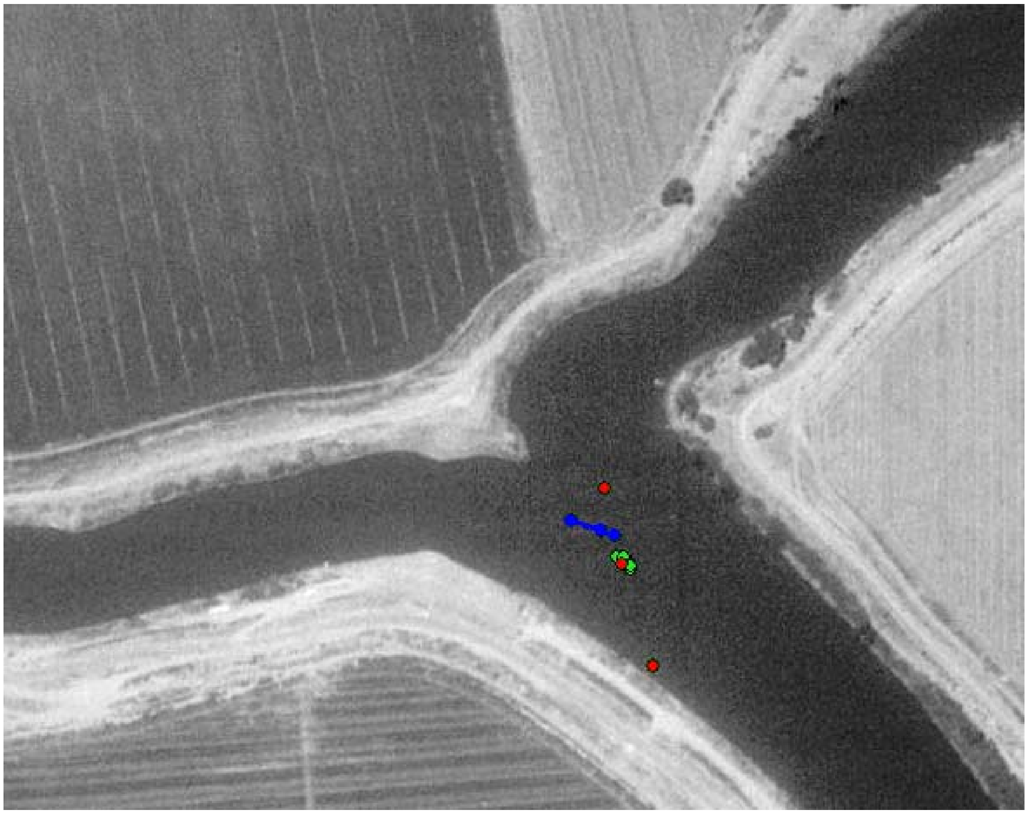


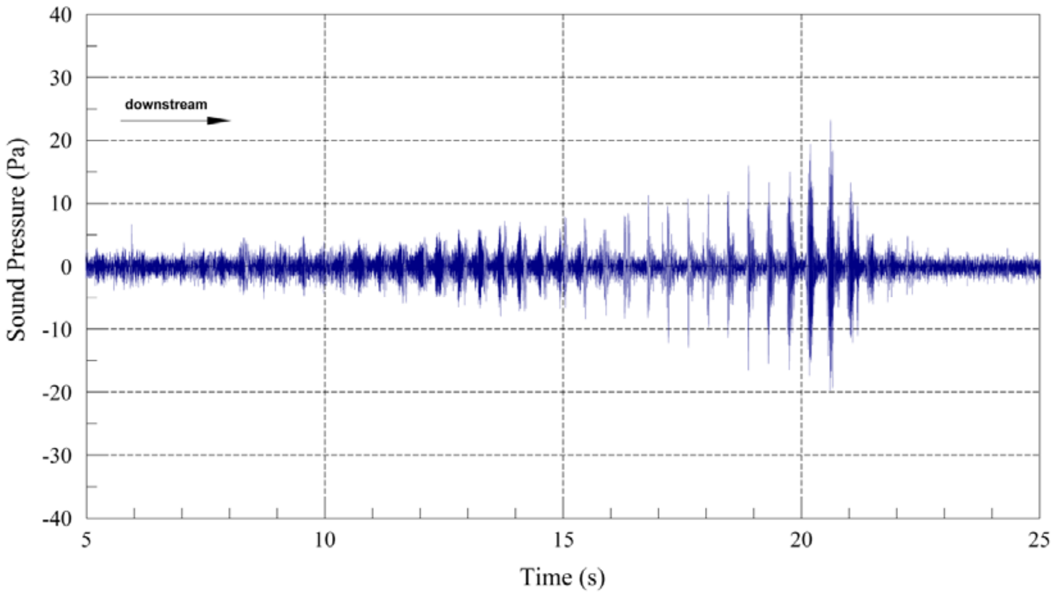
Figure A1. – GPS waypoints from measurement locations. Green points are upstream and downstream from Pile 2, red points are the location of the straight portion of the BAFF, Frames 1-13, and blue track is for the drift locations in Appendix B.

Table A 1. –Fixed sound measurements at/near Piling 2, hydrophone located 0.61 m above channel bottom in 2.5 to 3.1 m of water, flow measurements from Mossdale gage. Root Mean Square of Sound Pressure Level reported in Pascals (PA).

Location	Position (m)	Barrier Status	Discharge (m^3/s)	RMS Sound pressure (Pa)
Piling 2	5 – upstream	Off	163	8.146
Piling 2	3 – upstream	Off	163	File corrupt
Piling 2	1 – upstream	Off	163	File corrupt
Piling 2	1 – downstream	Off	170	6.029
Piling 2	3 – downstream	Off	170	10.057
Piling 2	5 – downstream	Off	170	11.646
Piling 2	5 – upstream	On	166	13.530
Piling 2	3 – upstream	On	166	12.619
Piling 2	3 – upstream	On	166	12.271
Piling 2	1 – upstream	On	166	45.582
Piling 2	1 – downstream	On	166	18.668
Piling 2	3 – downstream	On	162	14.887
Piling 2	5 – downstream	On	162	10.526
Piling 2	10 – downstream	On	162	6.660

Appendix B – Sound Pressure Recorded 0.3 M below the Water Surface as the Sampling Boat Drifts from Upstream of the BAFF to Downstream (See location of drift, blue points, in Figure A1)

Peak amplitudes are likely when the hydrophone is centered within the bubble plume.



Appendix C – Illuminance from 60 Second Integrations Using the ILT1700 Radiometer

Illuminance is the recorded in-water value at the distance (Position(m)) reported from the Bio-Acoustic Fish Fence. The ambient illuninance is the lux/s recorded in-air near the same location.

Location	Position (m)	Barrier Status	Illuminance (lux/s)	Ambient Illuminance (lux/s)
Piling 2	5 m – upstream	Day/Off	34.41	20935
Piling 2	3 m – upstream	Day/Off	18.42	20935
Piling 2	1 m – upstream	Day/Off	31.77	20935
Piling 2	1 m - downstream	Day/Off	55.61	88800
Piling 2	3 m – downstream	Day/Off	88.98	88800
Piling 2	5 m – downstream	Day/Off	86.29	88800
Piling 2	5 m – upstream	Day/ On	20.16	126293
Piling 2	3 m – upstream	Day/On	132.93	126293
Piling 2	3 m – upstream	Day/On	132.93	126293
Piling 2	1 m – upstream	Day/On	177.42	126293
Piling 2	1 m – downstream	Day/On	48.08	126293
Piling 2	3 m – downstream	Day/On	29.13	33349
Piling 2	5 m – downstream	Day/On	25.51	33349
Piling 2	10 m – downstream	Day/On	26.42	33349
Piling 2	10 m – downstream	Night/On	0.15	0.54
Piling 2	5 m – downstream	Night/On	0.94	0.54
Piling 2	3 m – downstream	Night/On	6.53	0.54
Piling 2	1 m - downstream	Night/On	163.43	0.54