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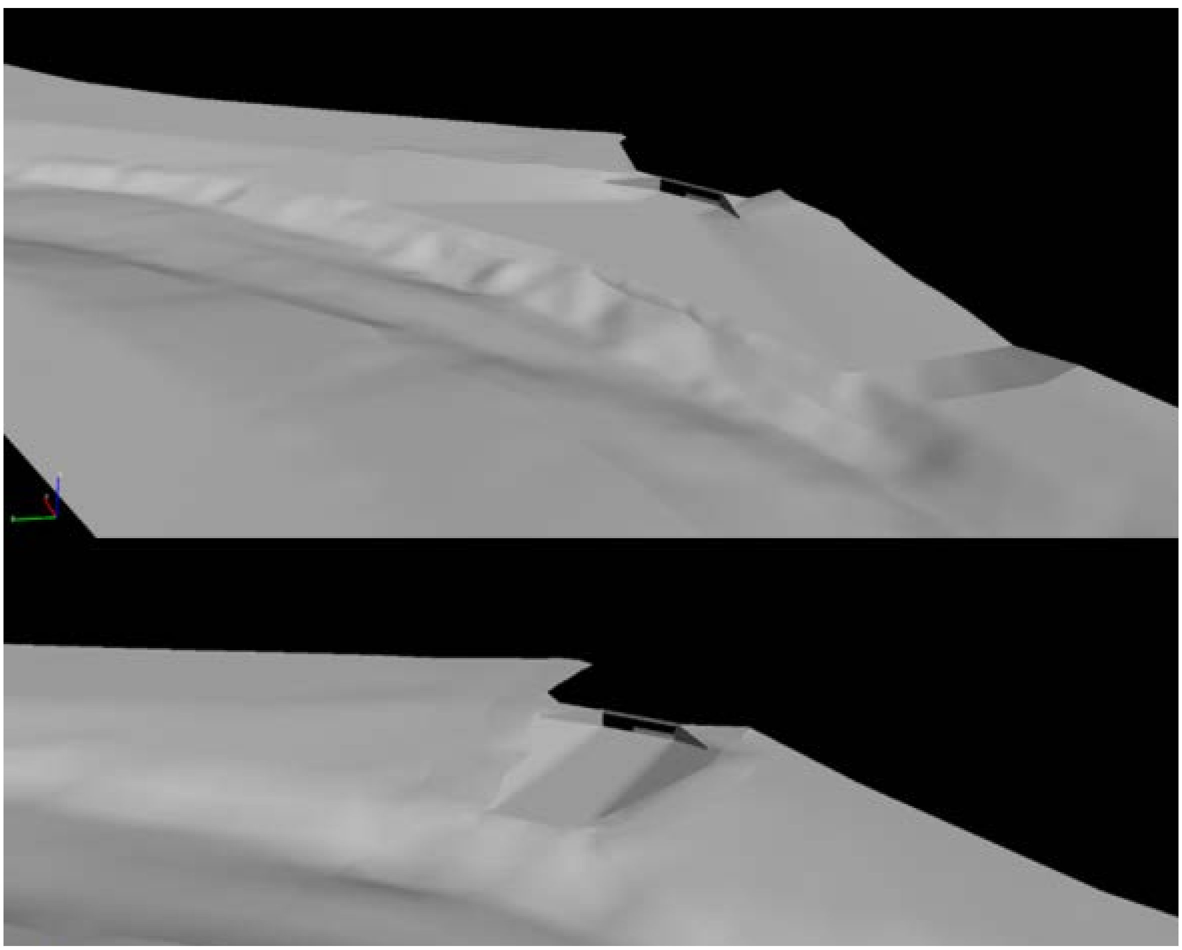
SCENARIO ANALYSIS OF FREMONT WEIR NOTCH – INTEGRATION OF ENGINEERING DESIGNS, TELEMETRY, AND FLOW FIELDS

David L. Smith, Tammy Threadgill, Bertrand Lemasson, Yong Lai, Anna Steel Christa Woodley, Amanda Hines, R. Andrew Goodwin, Josh Israel

July 2017



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Final report

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Abstract

The United States Bureau of Reclamation and the California Department of Water Resources are planning a notch in the Fremont Weir on the Sacramento River. The notch is intended to provide access to the Yolo Bypass floodplain for juvenile salmon across a range of flows and to provide passage for adult anadromous fishes, and to increase floodplain inundation. This study estimated the entrainment rate of 12 separate notch scenarios. Entrainment estimates vary from approximately 1 to 25%. Across all scenarios larger notch flows entrain greater fish numbers, although not proportionally to the volume through the notch. West located notches entrain more fish than central and east and intakes perform better than shelfs. However, intakes and shelfs both performed poorly, regardless of notch flows, when intake channels were angled from the mainstem. Entrainment estimates are comparable to measured entrainment rates elsewhere in the Sacramento River suggesting that the modeled estimates are reasonable. The results further suggest that the approach used is valuable for incorporating structural modifications and evaluating expected outcomes.

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Preface

This study was conducted for the United States Bureau of Reclamation using Interagency Agreement R13PG20203. The technical monitor was Dr. Patrick Deliman.

The work was performed by the Water Quality and Contaminant Modeling Branch (EPW) of the Environmental Processes and Effects Division (EP), US Army Engineer Research and Development Center, Environmental Laboratory. At the time of publication, Mark Noel was Acting Chief, CEERD-EPW; Warren Lorenz was Chief, CEERD-EP; and Pat Deliman, CEERD-EV-E was the Technical Director. The Deputy Director of ERDC-EL was Dr. Jack Davis and the Director was Dr. Beth Fleming.

COL Bryan Green was the Commander of ERDC, and Dr. David Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	Meters
miles (US statute)	1,609.347	Meters

1 Introduction

As California's largest river, the Sacramento River is an important economic, recreational, and ecological resource. The river has an extensive flood control infrastructure that includes a system of dams, levees, and floodways intended to protect agricultural and urban regions. In particular, the metropolitan area of Sacramento with some 2 million residents is protected from flooding by this system. Protection is due to levees but flood events are conveyed out of the river channels and onto floodways such as the Yolo Bypass. In addition to providing protection, the floodways receive sediment and nutrients and thus impact ecosystem processes including those associated with floodplain access by fish [1].

The Yolo Bypass is a 24,000 ha basin protected by levees and inundated during high flow on the Sacramento River. The floodway is 61 km long and is flooded approximately 7 out of 10 years with a peak flow of 14,000 m^3/s. Water is conveyed over the Fremont Weir onto the Yolo Bypass [2].

The Fremont Weir was constructed in 1924 by the U. S. Army Corps of Engineers. It is the first overflow structure on the river's right bank and its two-mile overall length marks the beginning of the Yolo Bypass. It is located about 15 miles northwest of Sacramento and eight miles northeast of Woodland. South of this latitude the Yolo Bypass conveys 80% of the system's maximum flows through Yolo and Solano Counties until it connects to the Sacramento River a few miles upstream of Rio Vista. The Fremont Weir's primary purpose is to release overflow waters of the Sacramento River, Sutter Bypass, and the Feather River into the Yolo Bypass. The crest elevation is approximately 32.0 feet (NAVD88) and the project design capacity of the weir is 343,000 cfs. Adding a notch will change the frequency/duration of water flowing onto the Yolo Bypass via flows through the notch channel, not over the Fremont Weir.

On June 4, 2009, the National Marine Fisheries Service (NMFS) issued its Biological Opinion and Conference Opinion on the Long-term Operation of the Central Valley Project (CVP) and State Water Project (SWP) (NMFS Operation BO). The NMFS Operation BO concluded that, if left unchanged, CVP and SWP operations were likely to jeopardize the continued existence of four federally-listed anadromous fish species: Sacramento

River winter-run Chinook salmon *(Oncorhynchus tshawytscha),* Central Valley spring-run Chinook salmon, California Central Valley steelhead (*O. mykiss*), and Southern Distinct Population Segment (DPS) North American green sturgeon (*Acipenser medirostris*). The NMFS Operation BO sets forth Reasonable and Prudent Alternative (RPA) actions that would allow SWP and CVP operations to remain in compliance with the federal Endangered Species Act (ESA). RPA actions include restoration of floodplain rearing habitat, through a "notched" channel that increases seasonal inundation within the lower Sacramento River basin. A significant component of these risk reduction actions is lowering a section of the Fremont Weir (Figure 1) to allow juvenile fish to enter the bypass and adult fish to more easily return to the Sacramento River. Questions remain on the details of notch implementation (e.g., size, location), fish entrainment efficiency, and species-specific and ontology-based behaviors.

Among actions being considered are alternatives to "increase inundation of publicly and privately owned suitable acreage within the Yolo Bypass." During inundation, the Yolo Bypass has been shown to have beneficial effects on growth of juvenile salmonids (Sommer et al. 2001) due to the favorable rearing conditions (e.g., increased primary productivity, relatively slow water velocities, abundant invertebrates). Entrainment of juvenile salmonids into the bypass routes them around the Delta, thereby minimizing the potential for entrainment by the pumps at the State Water Project and Central Valley Project. Therefore, maximizing entrainment into the bypass, particularly at lower stages, is of particular interest. Uncertainty exists about how the location, approach channel, and notch design and setting influence the effectiveness for entraining juvenile salmonids from the Sacramento River onto the Yolo Bypass.

It is generally recognized that fish are unevenly distributed across a channel cross section and that the position of the fish influences the probability that entrainment occurs [3]. The distribution of fish is in part related to secondary circulations which tend to concentrate passive particles such as sediment away from the channel margins and towards the bank of long radius of a river bend. This conceptual model is often applied to downstream movement of fish such as juvenile salmon in the Sacramento River. Notch entrainment efficiency is potentially improved by placing the notch where fish density is maximized along the outside bend. Of course, the specifics of the fish distribution are related to the unique attributes of each cross section, notch design, and the behavior of fish therein. The efficiency of an entrainment channel is the most important factor impacting fish benefits based on the Fishery Benefit Model (Hinkelman et al. in review).

In 2015, two-dimensional (2-D) positions were measured for hatchery late-fall and winter-run Chinook along a portion of the Fremont Weir. These tracks provided the basis for this study. The objective of this study was to validate an existing fish behavior model for use on this project, simulate a range of alternate notch designs, and evaluate the sensitivity on entrainment to different locations and designs. Additionally, this modeling approach allowed for exploration of different hypotheses regarding fish behavior and the influence they could have on movement and entrainment through the simulated notches. These results will evaluate the sensitivity on entrainment for different designs and locations along the Fremont Weir.

1.1 Fremont Weir

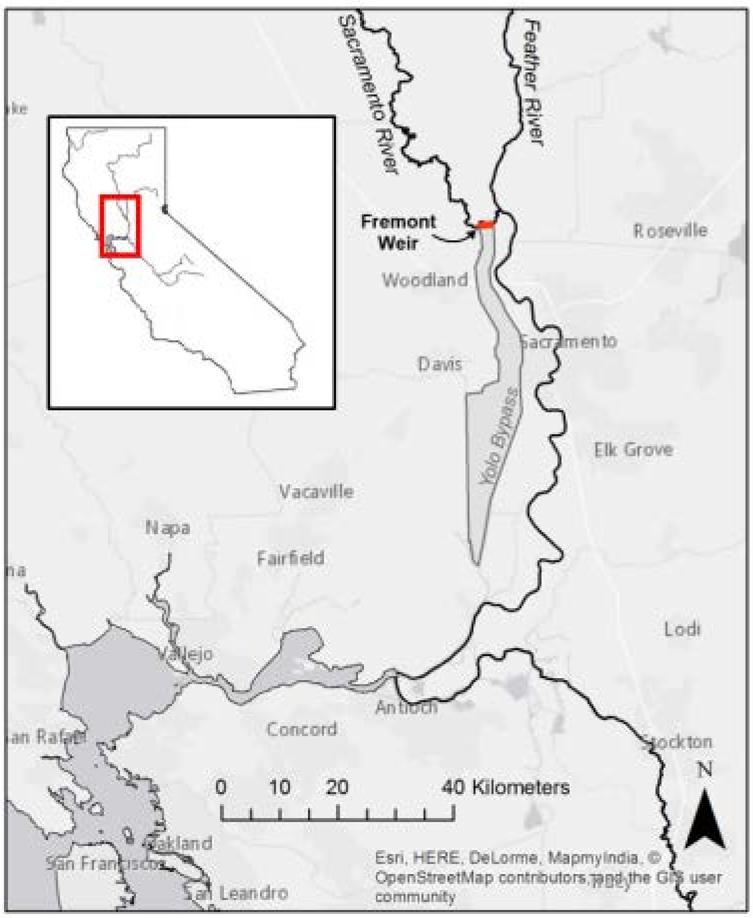
Fremont Weir is a 1.8-mile long flood control structure designed with a concrete, energy-dissipating splash basin, which minimizes scouring during overtopping events at the weir. The splash basin lies just downstream of the crest of the weir and spans the full length of the weir.

When the river stage is sufficiently higher than the weir, all juvenile salmonids that get entrained onto the Yolo Bypass are hypothesized to enter the bypass due to the overwhelming extent of Sacramento River flows being pushed out of the channel and onto the bypass. It is also hypothesized that during lower-stage overtopping events, when the Sacramento River is just barely above the crest of Fremont Weir, this effect is also the predominant cause of entrainment of Sacramento River fish onto the bypass. Overtopping events can vary in duration from just a few hours to several weeks, but are relatively short-lived compared with the resulting flooded footprint of the Yolo Bypass, which persists following the overtopping events. This footprint is a result not just of overtopping at the Fremont Weir, but substantial out-of-channel flows from four westside tributaries: Knights Landing Ridge Cut, Cache Creek, Willow Slough, and Putah Creek.

As part of RPA Action I.6.1, inundation flows from the Sacramento River onto the Yolo Bypass will occur at river flows lower than when the weir is overtopped, while species of interest are migrating past the Fremont Weir reach towards the Delta. It is during this period that the action aims to increase entrainment of salmonids. Acierto et al. (2014) evaluated the potential for entrainment based on proportion of flow entering the bypass and identified that it was potentially limited. Uncertainty exists about how fish utilize the channel for migration and rearing and their relationship to cross-channel flow patterns and secondary circulations. This study evaluates how these bathymetric and hydraulic structures may influence fish entrainment and flow relationships.

As part of Action I.6.1, Fremont Weir will be modified to allow seasonal, partial floodplain inundation in order to provide increased habitat for salmonid rearing and to improve fish passage. The same physical feature used for floodplain inundation flows will be used for juvenile fish entrainment. The primary modification of Fremont Weir will add a notch with one or more bays.

Figure 1. Map of project site.



2 Goals and Objectives

This study analyzes 12 notch scenarios in the Fremont Weir in terms of entrainment of juvenile salmon. The goal is to quantify the relative entrainment rates (between 0 and 1) across the suite of scenarios and to identify possible strategies for enhancing entrainment outcomes. This study does not predict future entrainment as models generally do not predict future outcomes so much as highlight trends. As there is no notch yet built, predictions of absolute entrainment rates risk missing any number of unforeseen variables driving the movement of complex animals like salmon in riverine systems. In a planning context, relative changes across scenarios are an accepted standard practice. The outcomes of this study will be one factor of the overall decision on which alternative is most suited for meeting the larger project objectives. Once the notch is constructed, evaluation studies will provide the opportunity for additional calibration and verification of model output.

The objectives of this study include the following:

- Develop a base fish movement data set under existing conditions (no notch). This work was completed as part of Steel et al (2017).
- Develop a calibrated three dimensional (i.e., U2RANS, a 3D Reynolds Averaged Navier-Stokes solver) and two dimensional (i.e., SRH-2D, Sedimentation and River Hydraulics-Two-Dimension) time varying hydrodynamic model of the project reach. This work was completed as part of Lai (2016).
- Integrate engineering designs of proposed notches into existing bathymetry and landscape (LiDAR) data capturing important differences in locations, widths, invert elevations, and construction techniques.
- Develop two dimensional flow fields for each of the scenarios that capture the hydraulic impacts of each unique notch.
- Calibrate a fish movement model using data from Steel et al (2017) and Lai (2016).
- Apply the calibrated fish movement model to the flow fields produced by each scenario and summarize estimated entrainment rates.
- Make recommendations on next steps and possible improvements.

3 Scenario Descriptions and Domain Development

3.1 Scenarios

A suite of twelve notch scenarios was developed by the California Department of Water Resources (DWR) and the United States Bureau of Reclamation (USBR). The scenarios fall into two broad categories: 1) those with an extensive shelf adjacent to the notch and 2) those with a narrow channel or intake leading to the notch headworks. The headworks are where fish will exit the Sacramento River and enter the Yolo Bypass. The shelf based scenarios have a larger project footprint than the intake based scenarios. The primary purpose of the headworks for the shelf and intake configurations is to create a hydraulic connection between the Sacramento River and the Yolo Bypass during lower flows in the Sacramento River than currently exists. The headworks will consist of the inlet transition, the control structure, and the outlet transition, and will control the diversion of flow (up to about 12,000 cfs) from the Sacramento River into the Yolo Bypass.

Scenario notch locations are concentrated in the west, central, and east portion of the Fremont Weir (Figure 2). Table 1 highlights the dimensions captured in the landscape model of each scenario. Each scenario is different in terms of size, location, notch invert elevation, and width. These differences are translated into the 2D simulation of the flow field which, in turn, translates into simulated fish movement.

Figure 2. Scenario notch locations

3.2 Domain development

An IGES (initial graphic exchange specification) file was received from the USBR for each of the scenarios. Upon receipt of these files, each file was loaded into Capstone and an STL (stereolithography) file was created of the intake area. Once the intake area had a mesh associated with it, the original STL file of the river and intake STL file were then merged to create one mesh that represented the mesh used for the scenario. The STL was exported as a 2dm file using Paraview and extraneous faces were removed from the dataset or modified to best work with SRH-2D.

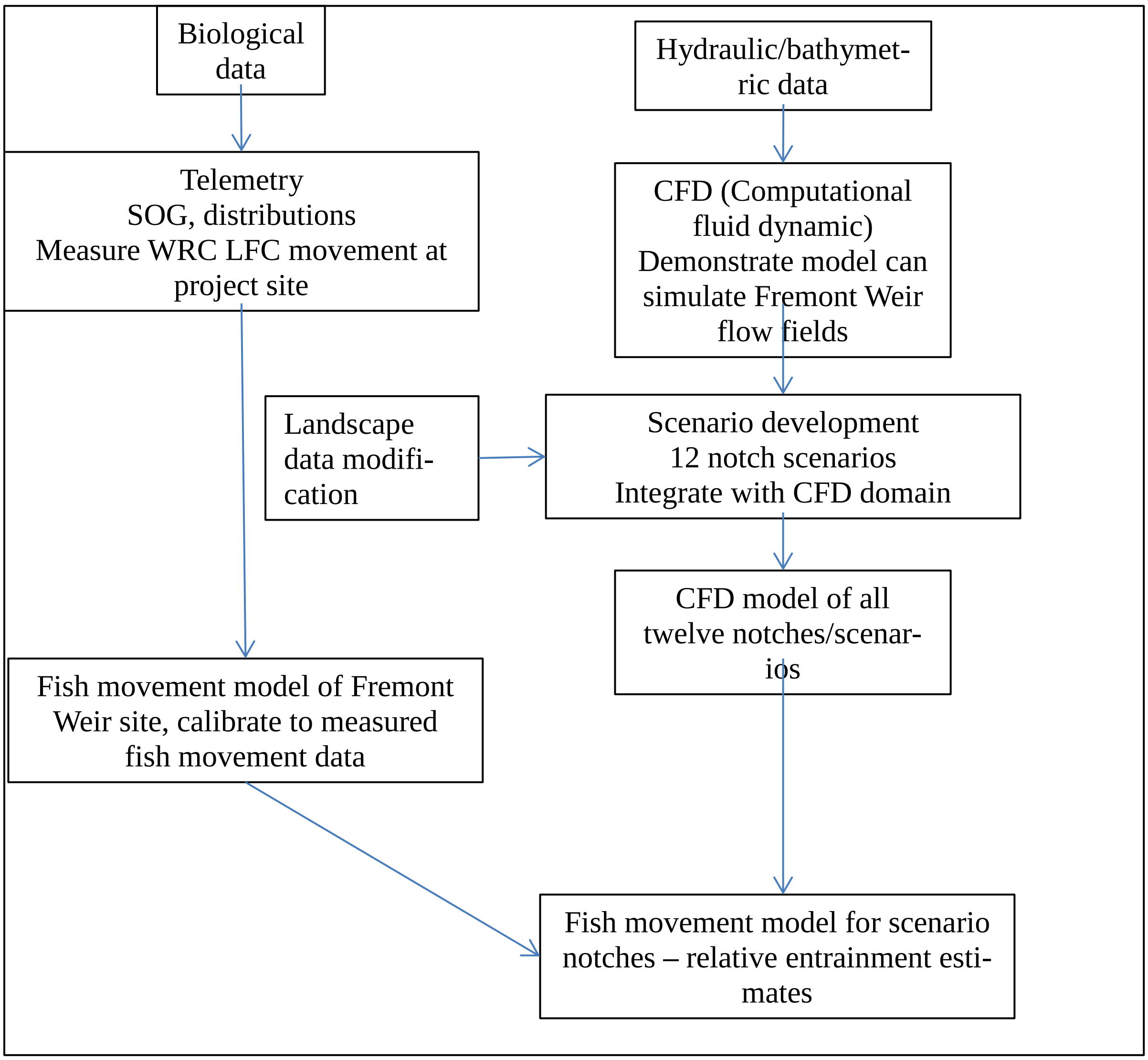
Table 1 Physical properties of modeled scenarios. Notch/River is the ratio of notch flow to river flow.

Scenario	Lower Intake		Upper Intake		# of Points	# of Elements	Notch Flow (cfs)	River Flow (cfs)	Notch/River
	Elevation	Width	Elevation	Width					
Original	NA	NA	NA	NA					
Scenario 1	14 ft	31 ft	20 ft	44 ft	31200	33924	6000.22	42202.51	0.14
Scenario 2	14 ft	32 ft	20 ft	44 ft	33427	36126	6000.22	42202.51	0.14
Scenario 3	17 ft	21 ft	23 ft	24 ft	32858	35596	3000.11	42202.51	0.07
Scenario 4	22 ft	14 ft	NA	NA	32913	35782	1105.75	48289.31	0.02
Scenario 5	14 ft	31 ft	20 ft	41 ft	31308	33702	5981.18	42202.51	0.14
Scenario 6	14 ft	32 ft	20 ft	43 ft	29238	32313	5952.99	44843.49	0.13
Scenario 7	14 ft	33 ft	20 ft	44 ft	37538	40628	6000.22	47957.43	0.13
Scenario 8	17 ft	21 ft	23 ft	25 ft	31115	33941	3000.11	47029.93	0.06
Scenario 9 – West	17 ft	21 ft	23 ft	37 ft	38372	41453	3000.11	47029.93	0.06
Scenario 9 – East	17 ft	21 ft	23 ft	25 ft			3000.11	47029.93	0.06
Scenario 10 – West (A/B)	14 ft	33 ft	17 ft	35 ft	42119	45016	480.91	30809.31	0.02
Scenario 10 – Central (C)	18 ft	142 ft	-	-	42119	45016	2379.52	30809.31	0.07
Scenario 10 – East (D)	21 ft	146 ft	-	-	42119	45016	542.32	30809.31	0.02
Scenario 11	16 ft	220 ft	-	-	34037	36504	12077.32	44843.49	0.27
Scenario 12	16 ft	40 ft	20 ft	60 ft	33288	35711	6105.22	47029.93	0.13

4 Study Design and Model Application

Developing a fish movement model to assist with scenario evaluation for the Fremont Weir notch requires integration of data and information from several sources and professional disciplines (Figure 3). The report used biological data from a telemetry study, hydrodynamic data and models, and landscape modeling techniques.

Figure 3. Workflow for development of fish movement model. SOG is speed over ground.



4.1 Fish telemetry

In 2015, 250 winter run Chinook (mean fork length of 103 mm) from Livingston Stone Hatchery and 250 late fall run Chinook (mean fork length of 145 mm) from Coleman National fish hatchery were tagged with acoustic tags and released through a detection area at Fremont Weir. The array was in a long sweeping bend located at the head of the upstream end of the Fremont weir. This location was thought to have the best conditions for redistributing fish to the outside bend where susceptibility to entrainment by a future notch would be higher. All fish were released over 24 hour periods at Knights Landing. River discharge was low and stable with gage readings at Fremont weir of approximately 14 ft and flows of approximately 5700 cfs. Analysis suggested little difference in movement between winter run Chinook and late fall run Chinook at Fremont weir. Speeds over grounds and size were not statistically different for winter and late fall run Chinook. The combined mean speed over ground was 0.67 m/s.

Cross-channel spatial distributions were also similar for winter and late fall run Chinook. There was a moderate shift in the spatial distribution to the outside bend of approximately 5 to 8 m away from the channel center. Chanel width is approximately 70 m with the centerline, therefore 35 m away from either bank.

Figure 4. Detection array at Fremont Weir

For more detail please refer to Steel et al. (2017) describes in detail the telemetry study that was completed to support work described in this report.

4.2 2D hydraulic models and landscape modeling

SRH-2D is a 2D depth-averaged hydraulic and sediment transport model for river systems. It was developed at the Technical Service Center, Bureau of Reclamation. The hydraulic flow modeling theory and user manual were documented by Lai (2008; 2010).SRH-2D was used for all hydrodynamic simulations used to support entrainment modeling.

SRH-2D adopts the arbitrarily shaped element method of Lai et al. (2003a, b), the finite-volume discretization method, and an implicit integration scheme. The numerical procedure is very robust so SRH-2D can simulate simultaneously all flow regimes (sub-, super-, and trans-critical flows) and both steady and unsteady flows. A special wetting-drying algorithm makes the model very stable in handling flows over dry surfaces. The mobile-bed sediment transport theory has been documented by Greimann et al. (2008), Lai and Greimann (2010), and Lai et al. (2011). The mobile-bed module predicts vertical stream bed changes by tracking multi-size, non-equilibrium sediment transport for suspended, mixed, and bed loads, and for cohesive and non-cohesive sediments, and on granular, erodible rock, or non-erodible beds. The effects of gravity and secondary flows on the sediment transport are accounted for by displacing the direction of the sediment transport vector from that of the local depth-averaged flow vector.

Major capabilities of SRH-2D are listed below:

- 2D depth-averaged solution of the St. Venant equations (dynamic wave equations) for flow hydraulics;

- An implicit solution scheme for solution robustness and efficiency;

- Hybrid mesh methodology which uses arbitrary mesh cell shapes. In most applications, a combination of quadrilateral and triangular meshes works the best;

- Steady or unsteady flows;

- All flow regimes simulated simultaneously: subcritical, supercritical, or transcritical flows;

- Mobile bed modeling of alluvial rivers with a steady, quasi-unsteady, or unsteady hydrograph.

- Non-cohesive or cohesive sediment transport;

- Non-equilibrium sediment transport;

- Multi-size sediment transport with bed sorting and armoring;

- A single sediment transport governing equation for both bed load, suspended load, and mixed load;

- Effects of gravity and secondary flows at curved bends; and

- Granular bed, erodible rock bed, or non-erodible bed.

SRH-2D is a 2D model, and it is particularly useful for problems where 2D effects are important. Examples include flows with in-stream structures such as weirs, diversion dams, release gates, coffer dams, etc.; bends and point bars; perched rivers; and multi-channel systems. 2D models may also be needed if certain hydraulic characteristics are important such as flow recirculation and eddy patterns; lateral variations; flow overtopping banks and levees; differential flow shears on river banks; and interaction between the main channel, vegetated areas and floodplains. Some of the scenarios listed above may be modeled in 1D, but additional empirical models and input parameters are needed and extra calibration must be carried out with unknown accuracy.

The 2D model was built and calibrated for the same conditions under which fish were released and their locations measured at Fremont Weir in 2015. This served as the base case. Refer to Lai (2016) for model specifics.

We represented each of the twelve scenario notch designs by integrating basic CAD designs into topography and bathymetry data. We used the Capstone software which is part of the DOD CREATE software suite. Capstone is a feature-rich application designed to produce analyzable representations of geometry for use with physics based solvers. In particular the geometry, mesh and associative attribution required for a computational simulation can be produced.

Geometry-related capabilities include:

- Geometry import and export for the IGES and STEP file formats
- Low-level geometry creation
- Edge and face splitting and merging
- Boolean operations
- Lofting, sweeping and extrusion
- Fillet and chamfer
- Various healing and stitching operations

Capstone excels at generating unstructured meshes for complex geometries. Due to the robust topology model, high-quality meshes can be generated for the manifold and non-manifold geometries often required in aerospace applications.

Meshing-related capabilities include:

- Mesh import and export for common formats including STL, CGNS, SURF and UGRID
- Mesh import and export for Create file formats including Kestrel (avm) and Sentri (Exodus)
- Robust and flexible sizing field
- Robust unstructured surface mesh generation
- Unstructured tet-dominant volume mesh generation
- Extruded boundary layer generation via the third-party AFLR volume mesher

- Sliding interfaces
- Mesh manipulation and repair operations
- Mesh export with associated attribution

One of the most important capabilities that Capstone provides is a framework for attributing a mesh based on the underlying geometry. For supported output formats the mesh is exported with associated attributes to be used in a physics-based analysis.

By integrating the CAD designs with existing landscape data and then modeling the 2D flow fields we captured the influence of notch details such as size, angle, step heights and the subsequent influence the local flow field and thus fish distribution and potential for entrainment.

Each of the notch designs are represented in Figure XC. Flows through the notch were represented using rating curves developed by the CA DWR. See Lai (2017)

4.3 Scenario descriptions

4.3.1 Scenario 1 West 6K Shelf

This scenario is located past the west end of the Fremont Weir. It has a minimum invert of 14 feet and a maximum flow of 6000 cfs. A broad shelf starts from the river and tapers toward the notch structure. The location is coincident with the Steel el al. (2017) fish movement study location.

4.3.2 Scenario 2 West 6K Intake

This scenario is located past the west end of Fremont Weir. It has a minimum invert of 14 feet and a maximum flow of 6000 cfs. A narrow intake channel starts from the river and leads toward the notch structure. Comparing Scenarios 1 and 2 allows for direct evaluation of the shelf versus intake approach. The location is coincident with the Steel et al. (2017) fish movement study location.

4.3.3 Scenario 3 West 3K Shelf

This scenario is located past the west end of the Fremont Weir. It has a minimum invert of 17 feet and a maximum flow of 3000 cfs. A broad shelf starts from the river and tapers toward the notch structure. Scenario 3 is most comparable to Scenario 1 with the exception of the minimum invert height. In addition, Scenario 3 and Scenario 1 have different rating curves leading to different notch flows at similar stages (Figure 5). The location is coincident with the Steel et al.(2017) fish movement study location.

4.3.4 Scenario 4 West 1K Shelf

This scenario is located past the west end of the Fremont Weir. It has a minimum invert of 22 feet and a maximum flow of 1,106. A broad shelf starts from the river and tapers toward the notch structure. Scenario 4 is placed in a similar location to Scenarios 1, 2 and 3. It is distinct because of the high minimum invert elevation and low maximum flow. Scenario 4 represents the smallest scenario in terms of concrete.

4.3.5 Scenario 5 Central

This scenario is in the central portion of the Fremont Weir located past the west end of the Fremont Weir. It has a minimum invert of 14 feet and a maximum flow of 6000 cfs. A broad shelf starts from the river and tapers toward the notch structure. Scenario 5 and Scenario 1 are similar in terms of size, have the same rating curve (Figure 5) and therefore allow comparison of the entrainment rate between the west and central positions. However, fish movement data were not collected in the Scenario 5 location in 2015. This reach has some remnant pilings, revetment and may require bank modification if constructed.

4.3.6 Scenario 6 East

This scenario is at the east portion of the Fremont Weir. It has a minimum invert of 14 feet and a maximum flow of 6000 cfs. A broad shelf starts from the river and tapers toward the notch structure. Scenario 6 is comparable to Scenario 1 in terms of terms of size, they have the same rating curve (Figure 5) and therefore allow comparison of the entrainment rate between the west and east positions.

4.3.7 Scenario 7 East

This scenario is in the east portion of the Fremont Weir. It has a minimum invert of 14 feet and a maximum flow of 6,000 cfs. A narrow intake channel broad shelf starts from the river and leads toward the notch structure. Scenario 7 is comparable to Scenario 6 and allows entrainment estimates between a shelf and intake style notch at the east location. In addition, Scenario 7 is comparable to Scenario 2 in terms of terms of size, they have the same rating curve (Figure X) and therefore allow comparison of the entrainment rate between the west and east positions. However, fish movement data were not collected in the Scenario 7 location.

4.3.8 Scenario 8 East

This scenario is in the east portion of the Fremont Weir. It has a minimum invert of 17 feet and a maximum flow of 3000 cfs. A broad shelf starts from the river and tapers toward the notch structure. Scenario 8 and Scenario 3 are comparable in terms of size and rating curves.

4.3.9 Scenario 9 East and West

This scenario has a structure located off of the west end of the Fremont Weir and in the east portion of the Fremont Weir. The east and the west structures are identical with minimum inverts of 17 feet and maximum flows of 3000 cfs each for a total of 6000 cfs. Both structures have a broad shelf that tapers to the notch. Scenario 9 has the same rating curves as Scenario 3 and 8.

4.3.10 Scenario 10 and 10B Central

This scenario has a three structure cluster in the central portion of the Fremont Weir. The structures combine to have a maximum flow of approximately 3400 cfs. The structures have a range of minimum inverts of 14, 18 and 21 feet. The structures are connected to the river with a narrow intake channel. Scenario 10B is structurally the same as 10 with some modifications to the underlying bathymetry and landscape model. Scenarios 10 and 10B are not readily comparable to other scenarios in terms of size, invert elevations and rating curves. Scenario 10 is most comparable to 10B and allows estimating entrainment as a function of terrain modification.

4.3.11 Scenario 11 West

Scenario 11 is located at the west end of Fremont Weir. Unlike Scenarios 1 through 4, which are set off the end of the Fremont weir, Scenario 11 placement is further downstream and intersects the Fremont weir structure. An intake channel leads from the river to the structure. Scenario 11 has a minimum invert of 16 feet and a maximum flow of 12,000 cfs. It is the largest structure in the study.

4.3.12 Scenario 12 West

Scenario 12 is located at the west end of Fremont Weir and like Scenario 11 intersects the Fremont weir structure. An intake channel leads from the river to the structure. Scenario 12 has a minimum invert of 16 feet and a maximum flow of 6,000 cfs. It is comparable to Scenario 1 in terms of size but has a different rating curve.

Figure 5. Rating curves for notches

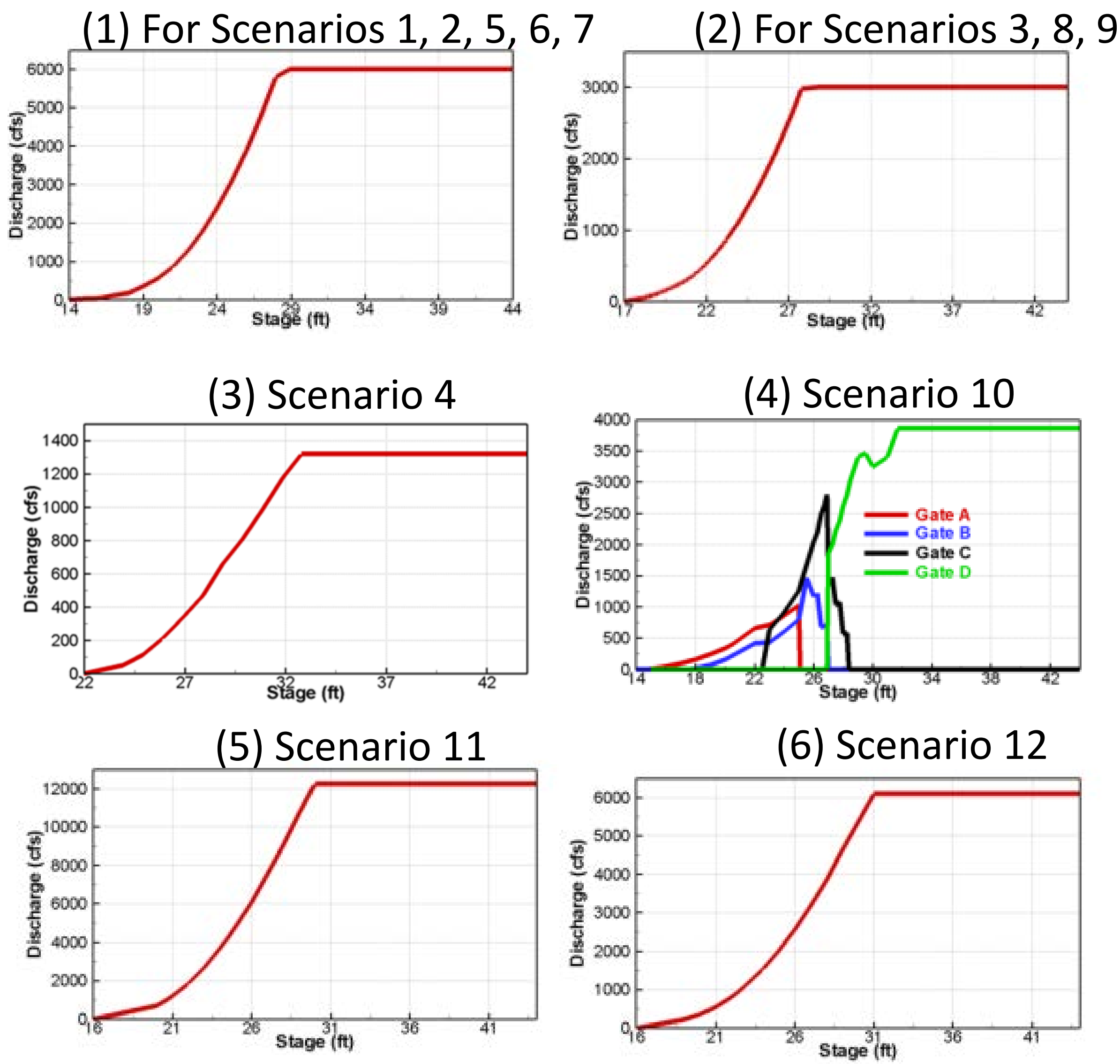


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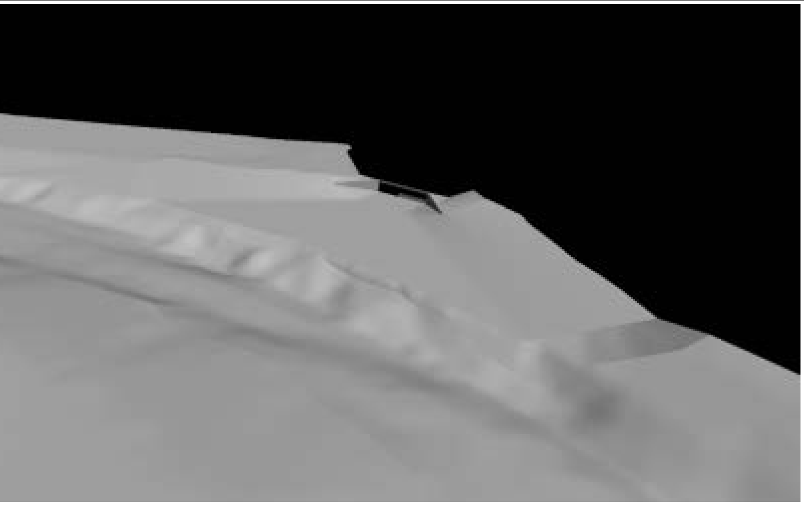
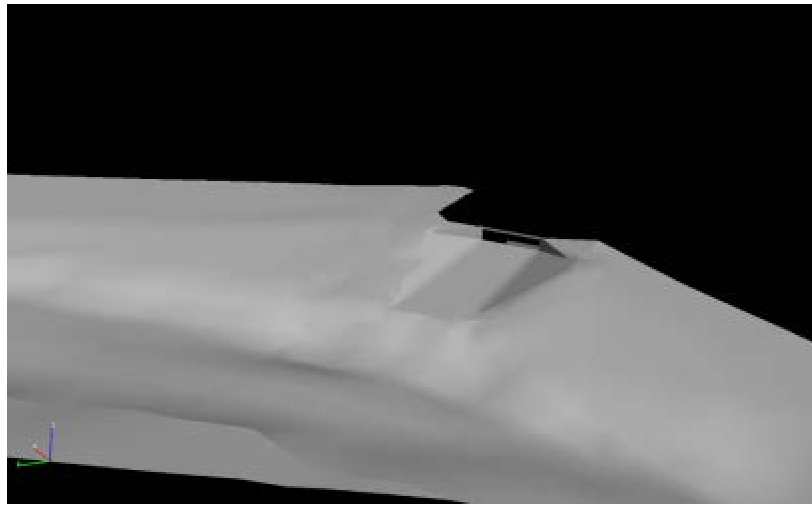
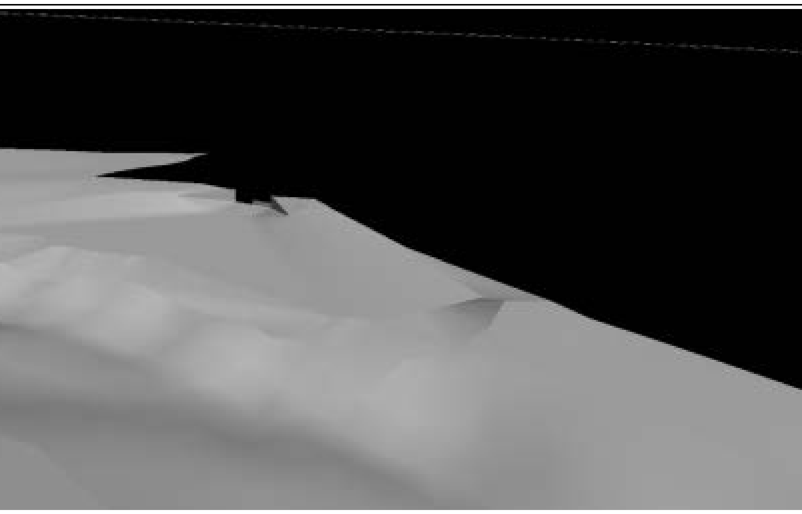
Figure 6. Images of notches as modeled.



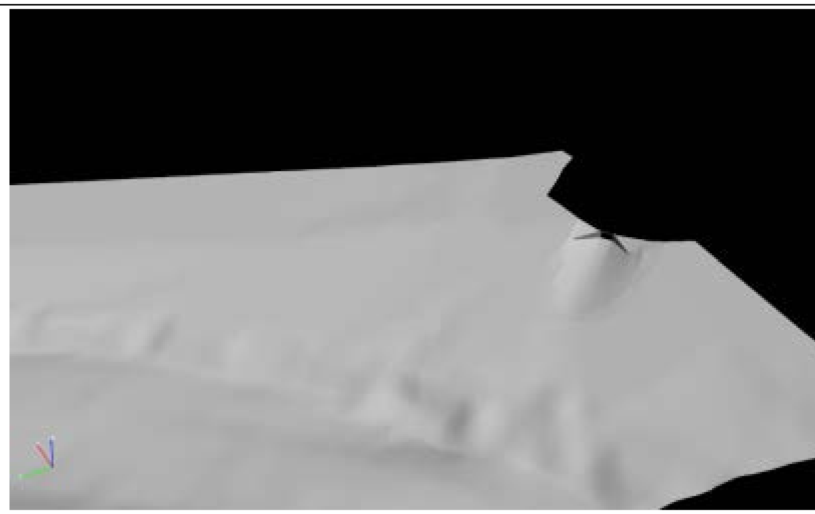
Scenario 1 – West - 6K – Shelf



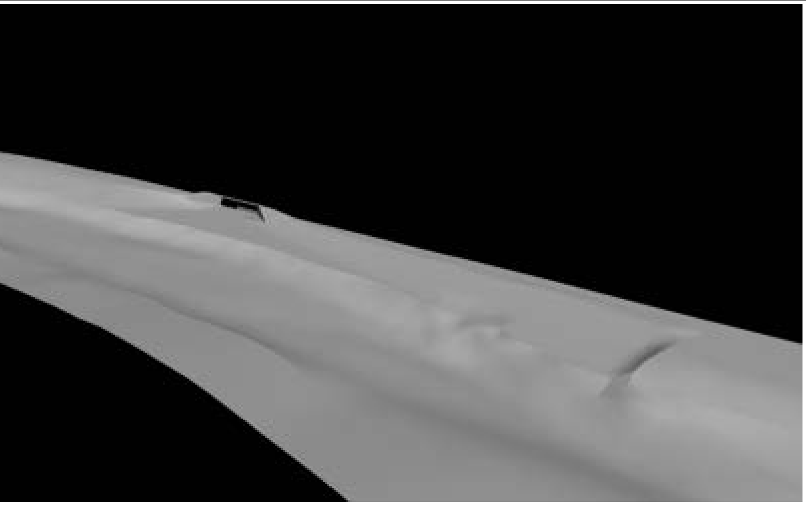
Scenario 2 – West - 6K - Intake



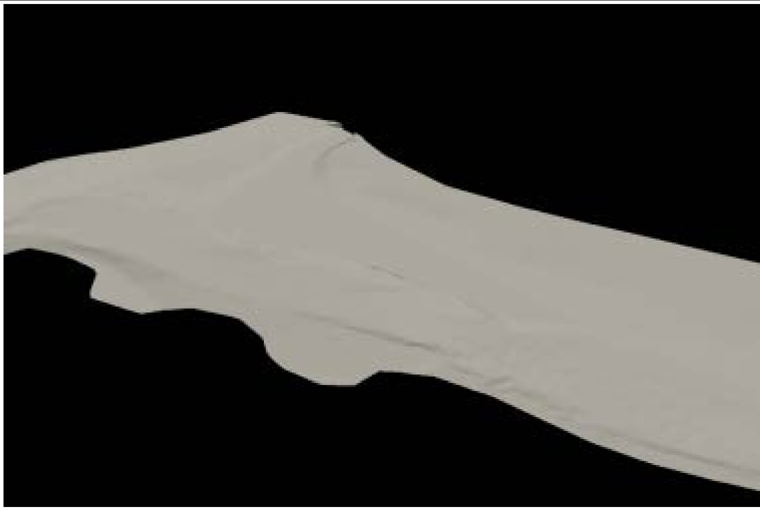
Scenario 3 – West - 3K – Shelf



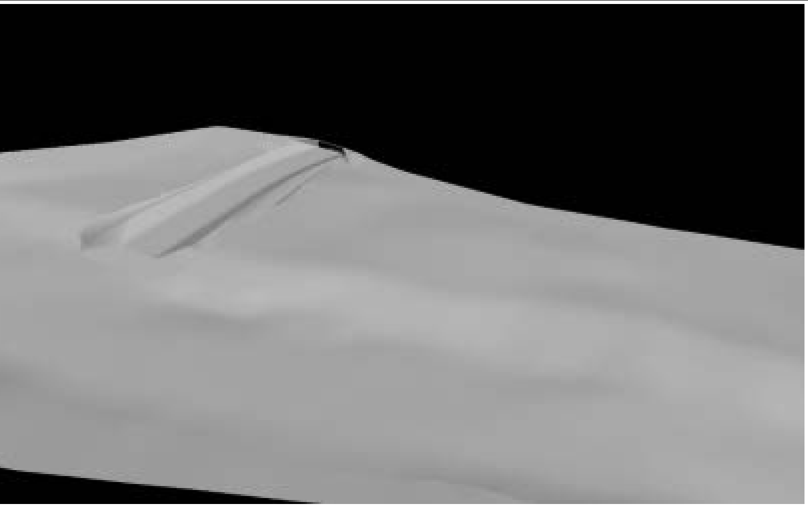
Scenario 4 – West - 1K - Shelf



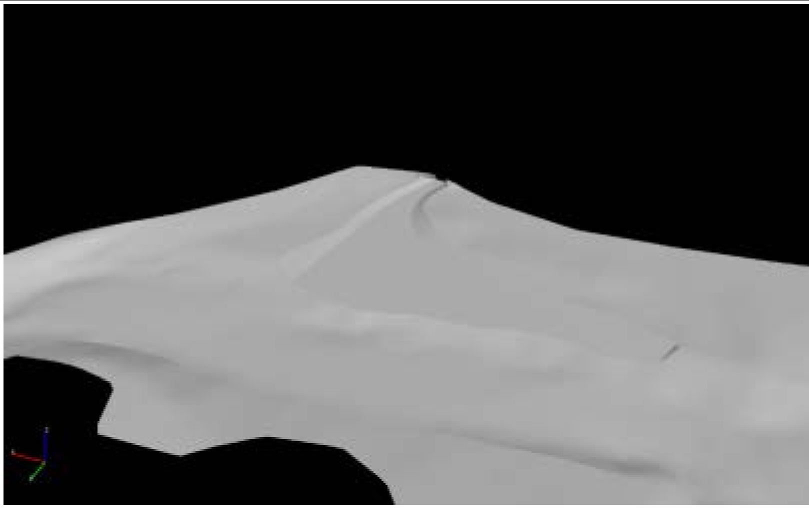
Scenario 5 – Central - 6K – Shelf



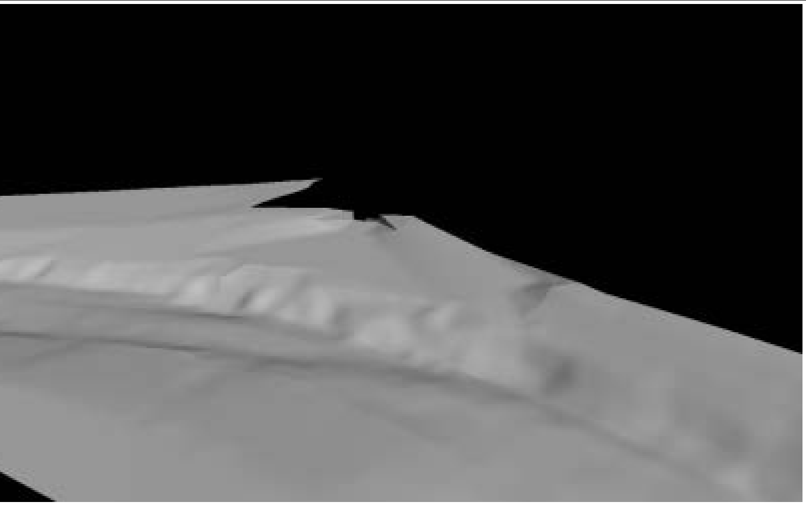
Scenario 6 – East - 6K - Shelf



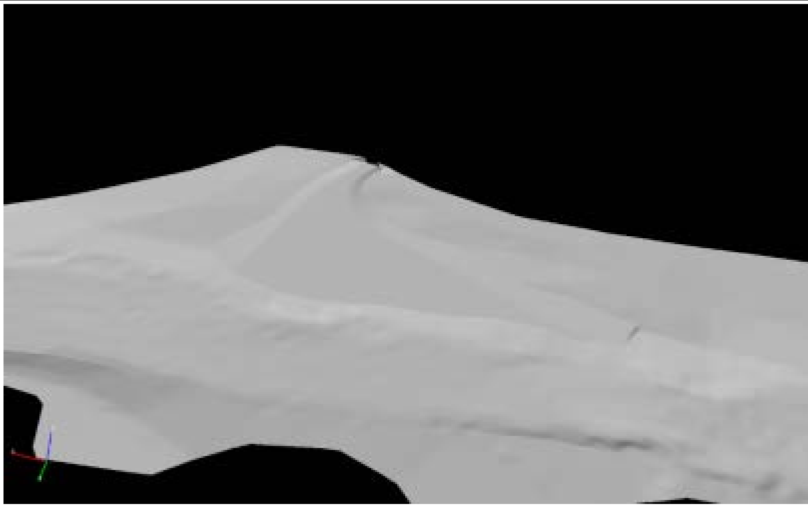
Scenario 7 – East - 6K – Intake



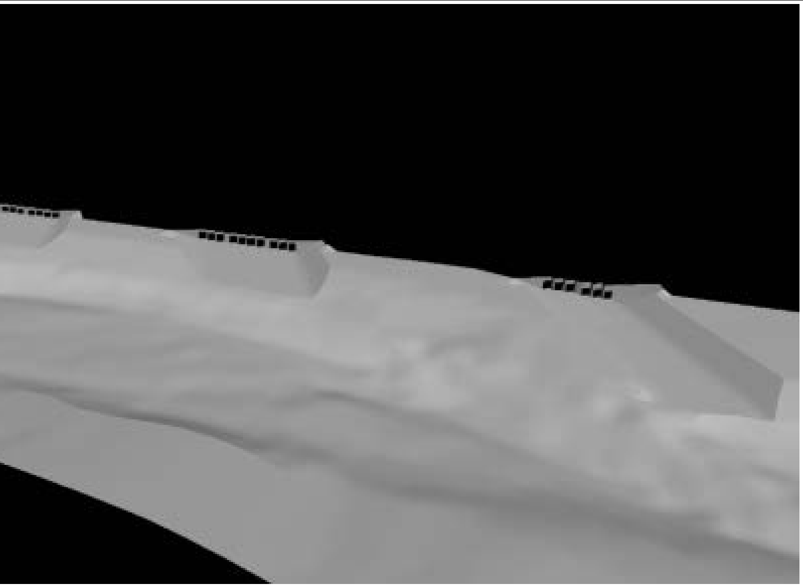
Scenario 8 – East - 3K - Shelf



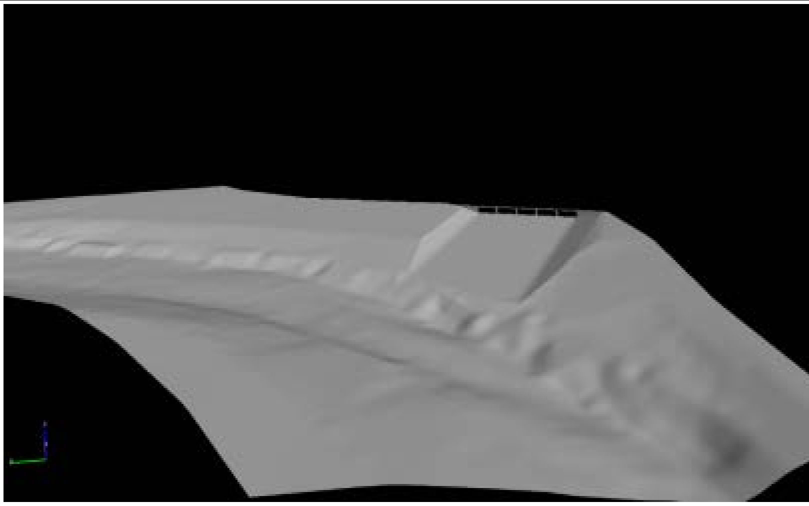
Scenario 9 – West - 3K – Shelf



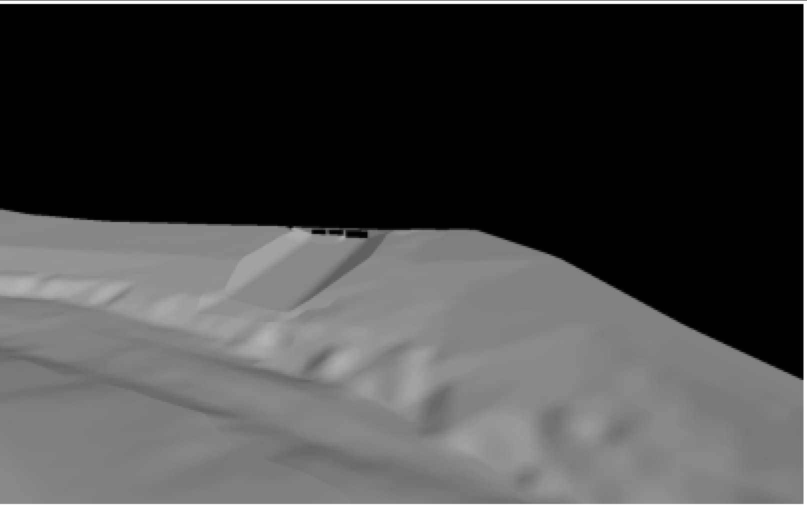
Scenario 9 – East - 3K - Shelf



Scenario 10 – Inundation - Central - 3K



Scenario 11 – Inundation - West - 12K



Scenario 12 – Inundation - West - 6K – Intake

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4.4 ELAM description

The ELAM (Eulerian-Lagrangian-agent Method) is a mechanistic representation of individual fish movement which accounts for local hydraulic patterns represented in computational fluid dynamic models (CFD) such as the 2D models developed for this project. Rule-based behaviors can be implemented within the model to drive fish movement. The model is agent based providing a mathematical means of representing the environment from the perspective of animal perception. The approach is informed by observations of fish movement such as what was collected at Fremont Weir (Steel et al. 2017) but individual tracks are not directly modeled. Rather, statistical properties of the measured tracks are used to guide model coefficient development. The approach supports extension of empirical observations toward unmeasured environmental conditions such as the wide scenario range evaluated as part of this project. The ELAM is documented in a number of publications (Appendix 1).

Hydrodynamic information generated at discrete points in the Eulerian mesh is interpolated to locations anywhere within the physical domain where fish may be. This conversion of information from the Eulerian mesh to a Lagrangian framework allows the generation of directional sensory inputs and movements in a reference framework similar to that perceived by real fish. Movement is treated as a two-step process: first, the fish evaluates agent attributes within the detection range of its sensory system and, second, it executes a response to an agent by moving (Bian 2003). The volume from which a fish acquires decision-making information is represented as a 2-D sensory ovoid. A virtual fish’s sense of direction at each time increment is based on its orientation at the beginning of the time increment. Directional sensory inputs are tracked relative to the horizontal orientation of the fish because fish response to laterally-located versus frontally-located stimuli can be different (Coombs et al. 2000). The sensory ovoid has a vertical reference because fish detect accelerations and gravitation through the otolith of its inner ear (Paxton 2000). It also senses three-dimensional information on motion (Braun and Coombs 2000). In this individual-based model (IBM) a symmetrical (spherical) sensory ovoid is used.

4.4.1 Movement

Two fish swim speeds were used: the drift velocity set at 0.25 BL/s and the cruising velocity of 1.5 BL/s. Fish speed variability was induced by calculating a random seed from a normal distribution centered on 0 with a standard deviation of 1 termed RRR (residual resistivity ratio). Swim speed variability was simulated by first calculating a deviation as

$$\sigma = RRR * Crusie - Drift$$

where cruise is the cruising velocity and drift is the drift velocity. Next the swim speed is computed as

$$Speed = BL * (Crusie + \sigma)$$

Many behaviors can be implemented within the ELAM. For this study only one behavior, a biased random walk in the downstream direction was used. The 2015 Fremont Weir fish movement data suggest no additional behaviors are represented.

The Ornstein-Uhlenbeck (OU) process was used to simulate sensing and orientation in the fish, i.e. how straight or variable a fish track composed of multiple sequential points is. The process was implemented by first calling a random seed from a wrapped uniform distribution. Two coefficients, $lamda\_xy$ and c_xy are used to calibrate computed fish positions using measured fish positions as a guide. Sensing describes the ability of the fish to locate the proper swim direction. For example, $lamda\_xy = 1$ would be perfect sensing ability and the fish would always know which movement direction was correct. On the other hand, c_xy represents the orientating ability with a value of 0 being perfect.

4.5 Fish movement modeling procedure

There were 13 separate hydraulic models representing the base condition and 12 scenarios. The base condition matched the location, discharge, and stage under which late fall and winter run chinook were tagged and released in 2015. Thus the base condition was used to calibrate the fish movement model. The calibration was done using 2D depth averaged hydraulic models. This was done in lieu of 3D hydraulic models for two reasons: First, the telemetry data is also 2D due to technology limitations of the telemetry gear that was used and second, since there were twelve scenarios to be considered, developing 3D models was time and cost prohibitive. Additional 3D models may be developed in the future if required for particular questions.

For calibration, fish were released in the model at Knights Landing. A total of 500 particles or fish were placed in a lateral cross section. The fish length was set to the mean size of fish released as part of Steel et al. (2017) equaling 124 mm. No differentiation in the fish movement model is made between late fall chinook and winter run chinook. Fish moved downstream, passed through the Fremont Weir reach, and exited the model at Verona.

Fish movement model data were post processed to produce speed over ground (SOG) and spatial distributions (kernel densities) using JMP (John's Macintosh Project software) 2012. The estimates were compared to the measured data, adjustments made to model parameters, and the model rerun until measured and computed values were similar. The two coefficients $lamda\_xy$ and c_xy were adjusted to approximate the speed over ground and spatial distribution through the project reach. Coefficient $lamda\_xy$ was set to 0.1 and c_xy was set to 2.0. Speed was insensitive and spatial distribution was sensitive to the parameters.

The calibrated model was then run for the twelve proposed scenarios and the proportion of fish entering the notch versus exiting the model domain at Verona was computed. Ten to thirty runs each with 500 fish were completed in order to estimate model variability. Each run was made with a different random seed to start the model. Higher levels of variability were possible by adjusting calibrated model parameters but results begin to differ from measured results. Thus, for the final runs we only modified the random seed.

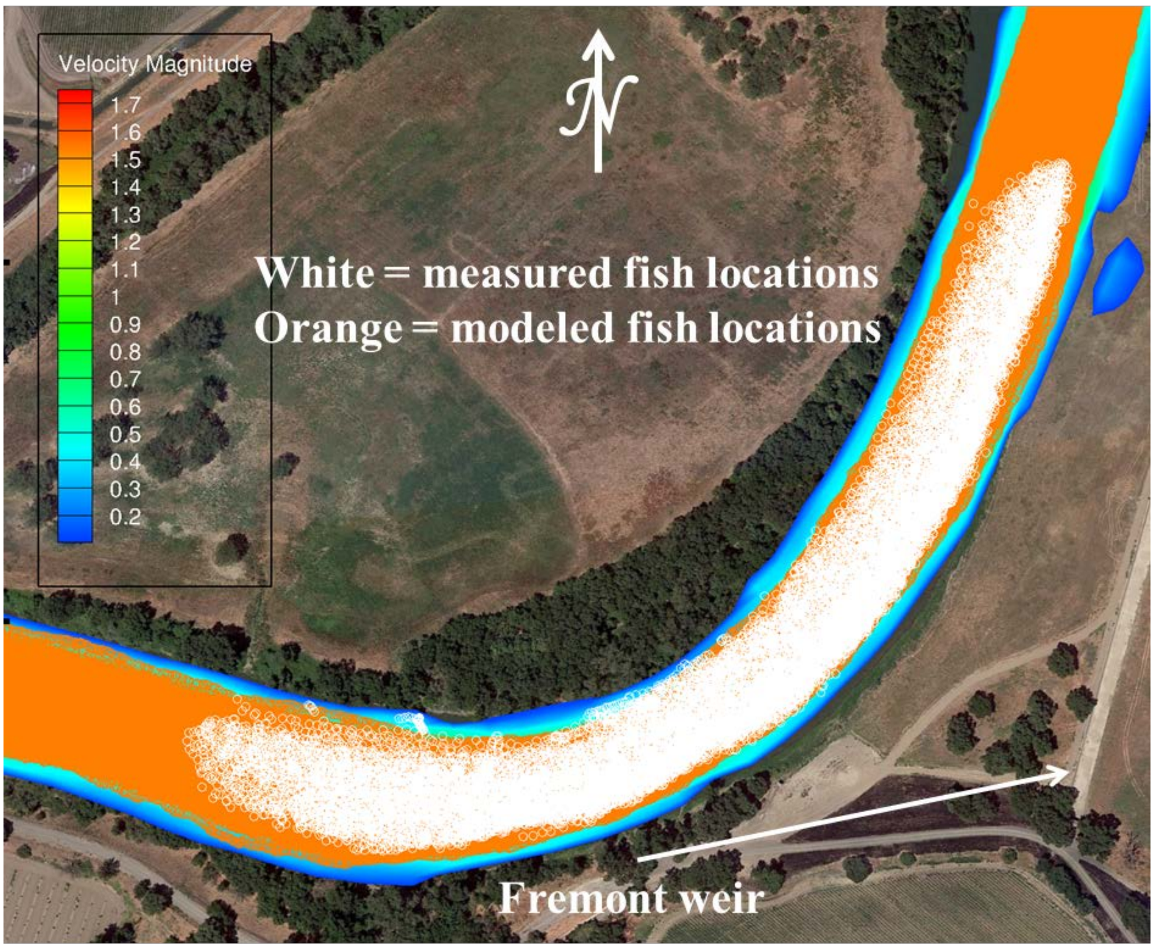
Estimates of entrainment percentages for each scenario were made for the maximum anticipated notch flow ranging from 1,000 to 12,000 cfs. Additional analysis was done for Scenarios 1 and 2 representing an intake and shelf style notch respectively. The analysis required running across a range of anticipated notch flows and estimating the entrainment for each. In addition, Scenarios 10 and 10B involved three separate structures and a complicated rating curve. Additional analysis for 10 and 10B across a range of flows was also done.

5 Results

5.1 Spatial distribution

Spatial distribution was assessed qualitatively by overlying measured fish positions from Steel et al. (2017) with modeled fish tracks (Figure 7). Tracks overlapped and have similar cross channel distributions.

Figure 7. Measured and Modeled Fish Locations

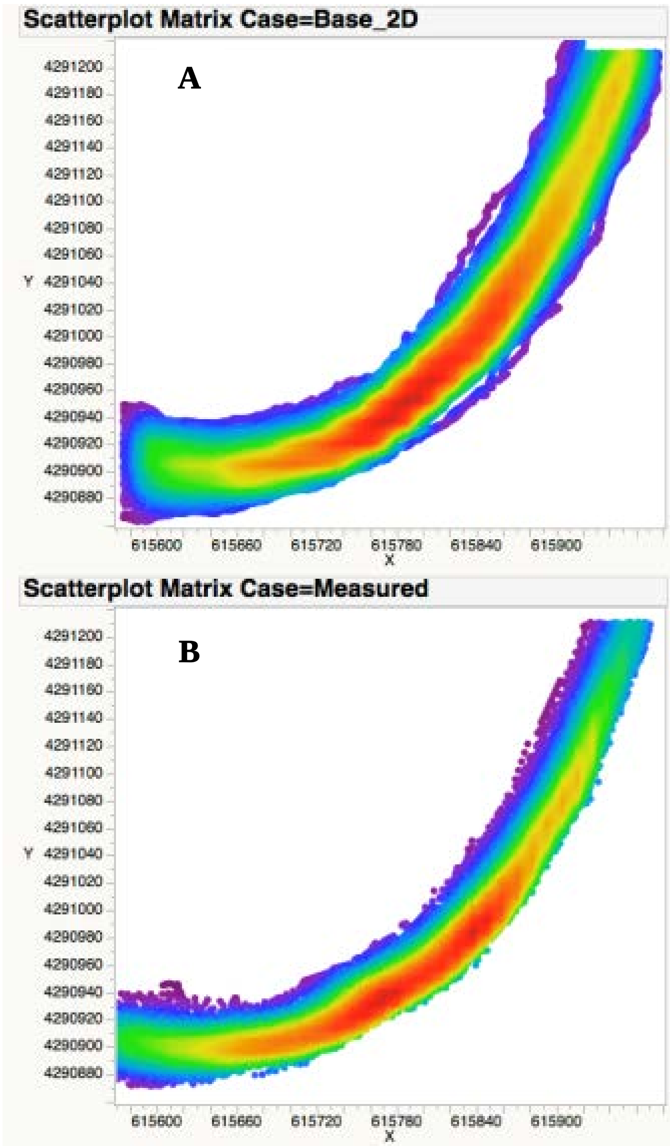


5.2 Kernel density estimates

Kernel densities for the measured and modeled fish distributions were calculated (Figure 8). Bivariate density estimation models a smooth surface that describes how dense the data points are at each point in that surface.

The plot adds a set of contour lines showing the density (Figure 8). Optionally, the contour lines are quantile contours in 5% intervals with thicker lines at the 10% quantile intervals. This means that about 5% of the points are below the lowest contour, 10% are below the next contour, and so forth. The highest contour has about 95% of the points below it.

Figure 8. Contour lines showing the density speed estimates for modeled (A) and measured fish positions (B)

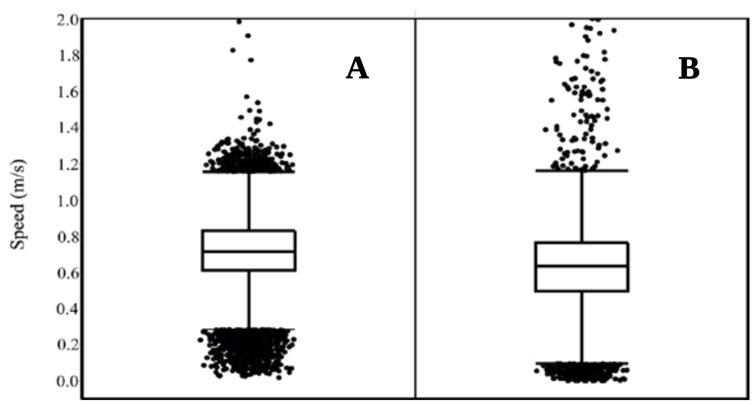


This nonparametric density method requires 1) dividing each axis into 50 binning intervals, for a total of 2,500 bins over the whole surface, 2) counting the points in each bin, 3) decide the smoothing kernel standard deviation (handled in JMP), 4) run a bivariate normal kernel smoother using an FFT (fast Fourier transform) and inverse FFT to do the convolution, and 5) create a contour map on the 2,500 bins using a bilinear surface patch model.

5.3 Speed Estimates

Speed over ground was computed for measured and modeled fish. Modeled fish estimates were based on 500 individual particles. Fish were released at Knights Landing Bridge and exited the domain at Verona. The resulting data set was subsampled to capture track data corresponding to the measured fish position data. Fish speed was computed for each fish and represented as a box plot (Figure 9). Modeled fish speed was 0.71 m/s and measured fish speed was 0.67 m/s with arrange of 0 to 2.o m/s.

Figure 9. Box plot of fish speed for modeled (A) and measured (B) fish speed over ground estimates.



5.4 Entrainment across all scenarios

Entrainment, as depicted in Figure 11, varied as a function of notch type (intake versus shelf), location (west, central, or east weir) and notch flow volume (cfs). Scenarios 1 (shelf) and 2 (intake) had entrainment rates of approximately 8% with Scenario 2 slightly superior to Scenario 1. Both Scenarios 1 and 2 have a maximum notch flow of 6,000 cfs. In contrast, Scenarios 3 and 4, while in the same location as Scenarios 1 and 2, have entrainment estimates of approximately 5 and 1% respectively. However, it is important to note that Scenarios 3 and 4 have higher invert elevations and lower notch flows when compared to Scenarios 1 and 2.

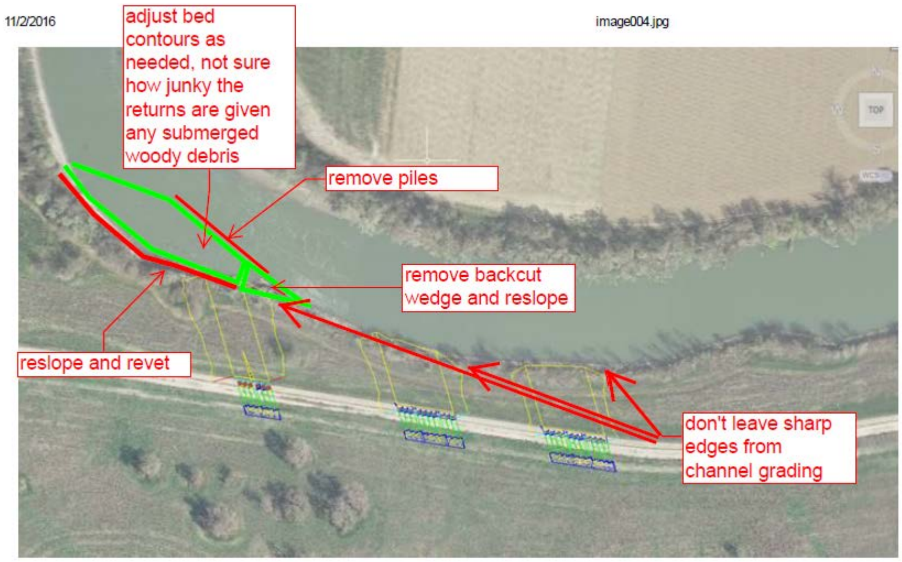
Scenario 5 is located in the central portion of the Fremont Weir but is otherwise similar to Scenario 2. Scenario 5 entrains approximately 4%. Scenario 5 is the only single notch structure evaluated for the central Fremont Weir location. Scenarios 10 and 10B structures are in a similar location and are described below.

Scenarios 6 through 8 are all located on the east portion of Fremont Weir. Scenarios 6 and 7 entrain approximately 5%, and Scenario 8 entrains approximately 2%. Like Scenarios 1 and 2, Scenarios 6 and 7 are a direct comparison of an intake versus shelf. Like Scenarios 1 and 2, Scenarios 6 and 7 have similar entrainment estimates. Compared to Scenarios 1 and 2, Scenarios 6 and 7 have lower entrainment estimates. Scenario 8 is directly comparable to Scenario 3 with the exception of its location on the east portion of Fremont Weir. Both Scenarios 3 and 8 have approximately 2% entrainment.

Scenario 9 is a combination of Scenarios 3 and 6 with one structure located on the west portion and one located on the east portion of Fremont Weir. Scenario 9 has an approximately 2% entrainment rate similar to

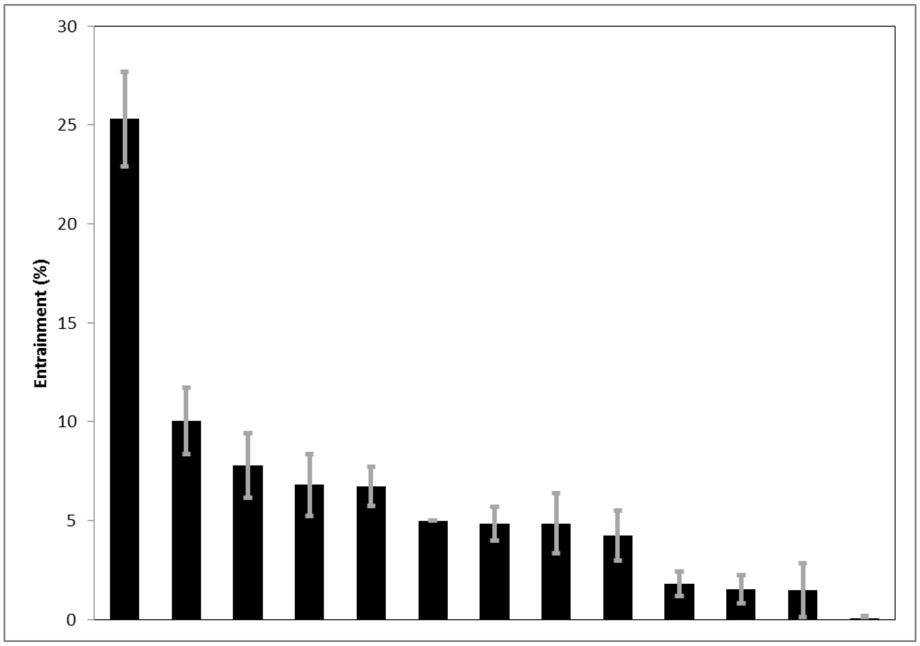
Scenario 3 or Scenario 6 alone.

Figure 10. Modifications completed for Scenario 10B based on email from Josh Urias to David Smith, 12/2/2016



Scenario 10 was similar to Scenarios 5, 6, and 7 at a flow of 3402 cfs. Scenario 10B was modified based on correspondence with Josh Urias, CA DWR (Figure 10). The modification required generating a new spatial model and running the 2D hydraulic model to produce the new flow fields. We attempted to capture as much of the input as possible. We modified the bathymetry and resloped the bank. We flattened the bathymetry signal from the existing piles and we softened the edges of the intake structure to round them. The resulting flow field and subsequent entrainment estimates were improved over Scenario 10 with approximately 10% of the fish entrained at 3402 cfs.

Figure 11. Mean entrainment estimates for each scenario at maximum flow with standard deviations. Scenario number is placed above each error bar.



Scenario 11, with the flow of 12,000 cfs entrained the greatest number of fish at approximately 25%. Scenario 12 is comparable to Scenario 2 as both are intake style notches. Entrainment rates for both are approximately 7%.

5.5 Flow and entrainment relationships

The following figures are all referenced to stage at Fremont Weir (ft, NAVD88). In most cases higher stages mean more notch flow and lower stages mean less notch flow.

For Scenario 1 (shelf) and Scenario 2 (intake) entrainment was modeled for a range of flows to establish the notch entrainment trends over the range of expected operating conditions. Scenarios 1 and 2 were chosen because each is located in the reach where fish were tracked in 2015. The hydrograph from the time period of December 1 to December 30 2015 was used as it contained both low and high river flows (represented as stages from Fremont Weir gage) needed to capture the full range of notch entrainment and was also used for the base model. The figures are entrainment estimates for simulated fish for Scenarios 1 and 2 at Fremont Weir across a range of notch flows and stages. Each data point is the mean entrainment rate at each notch flow. Error bars are the standard deviation based on a minimum of 6 runs of 500 fish each. Entrainment increases with stage for both but the transition from low entrainment (~1%) versus high entrainment (~8%) is slower for the shelf. Both scenarios entrain similar percentages of fish but Scenario 1 (shelf type notch) uses less water to achieve maximum entrainment.

Figure 12. Scenario 1 shelf

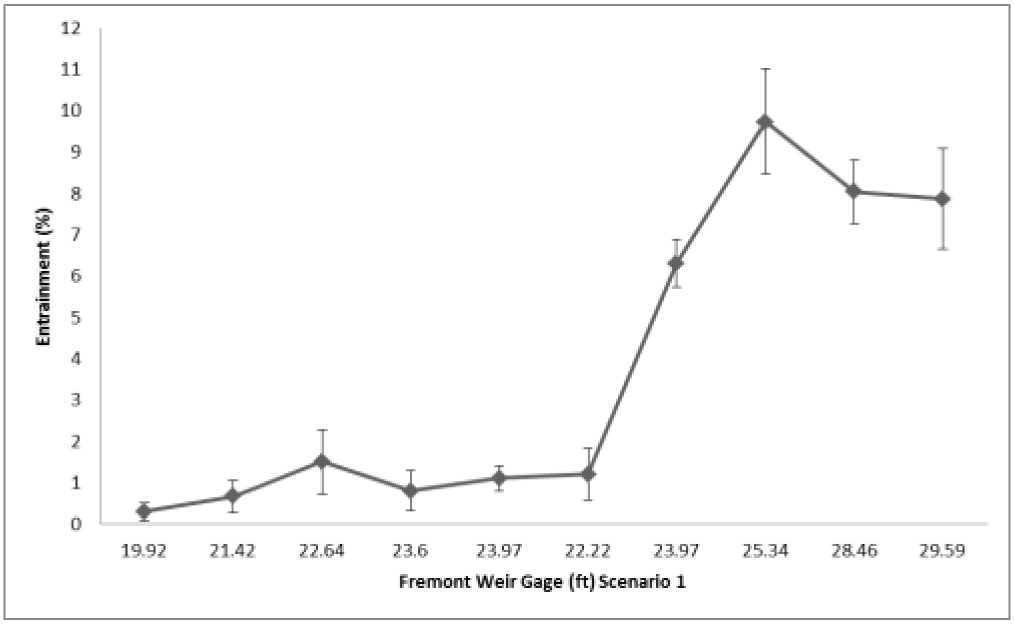
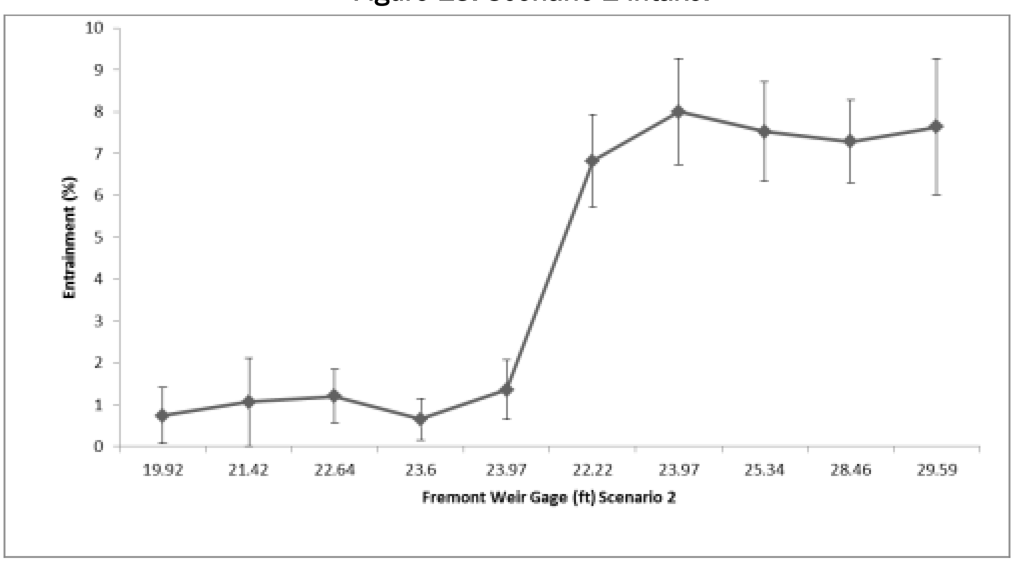
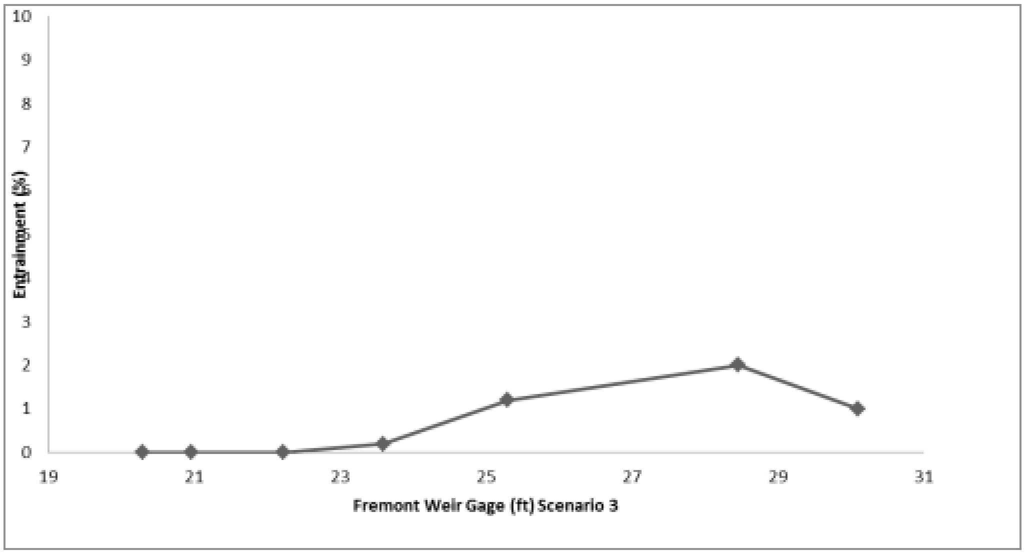


Figure 13. Scenario 2 intake.



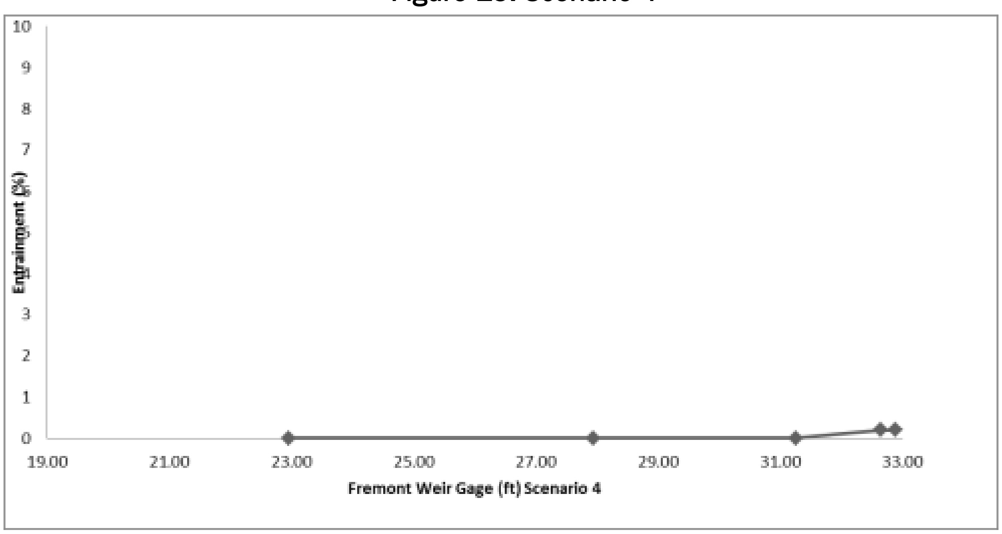
The error bars suggest that the mean estimated entrainment will vary up to approximately 3% based on the standard deviation around the mean. For example, a mean estimate of 10% could have a standard deviation ranging from approximately 13% to 7%. Error estimates for entrainment are not complete due to the late submission of ELAM scenarios. Error bars are expected to be similar to what has already been reported. Scenario 3 (Figure 14) entrains relatively few fish over the range of flows evaluated with the trend suggesting maximum entrainment of approximately 1 to 2% from 1500 to 3000 cfs.

Figure 14. Scenario 3



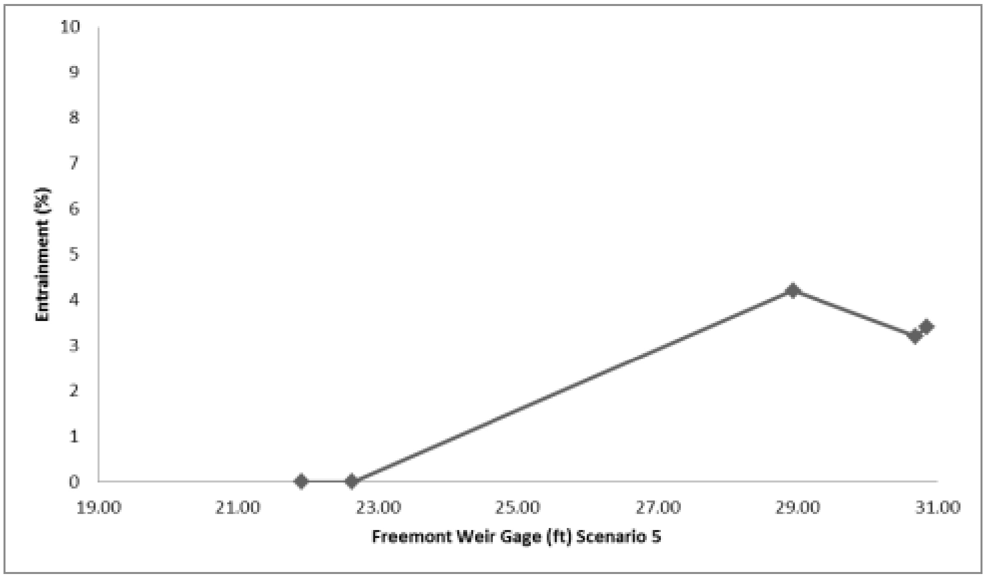
Scenario 4 (Figure 15) provides the lowest flow and entrainment across flows remains below 1%.

Figure 15. Scenario 4



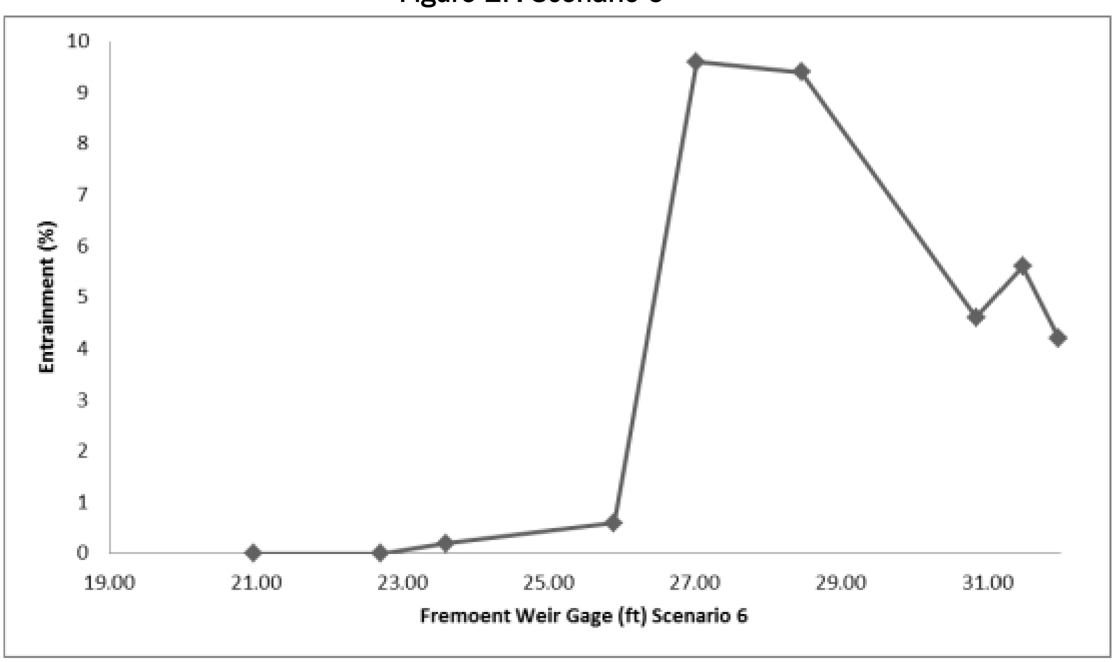
Scenario 5 (Figure 16) has a peak entrainment of approximately 5 % and reaches a plateau near 5000 cfs (approximately 29 ft at Fremont Weir gage)

Figure 16. Scenario 5



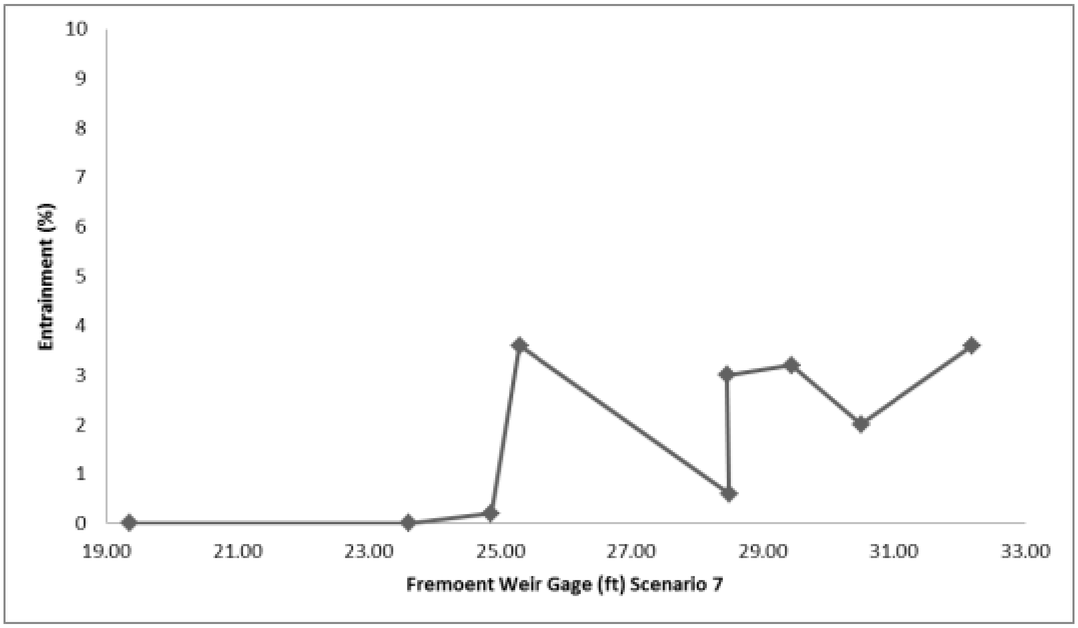
Scenario 6 (Figure 17) reaches a peak entrainment of approximately 10% at approximately 3000 cfs or half of the rated maximum notch flow. This appears to be related to the interaction of the excavated bench and stage that tends to diminish near bank recirculation zones and promote direct streamlines along the bank.

Figure 17. Scenario 6



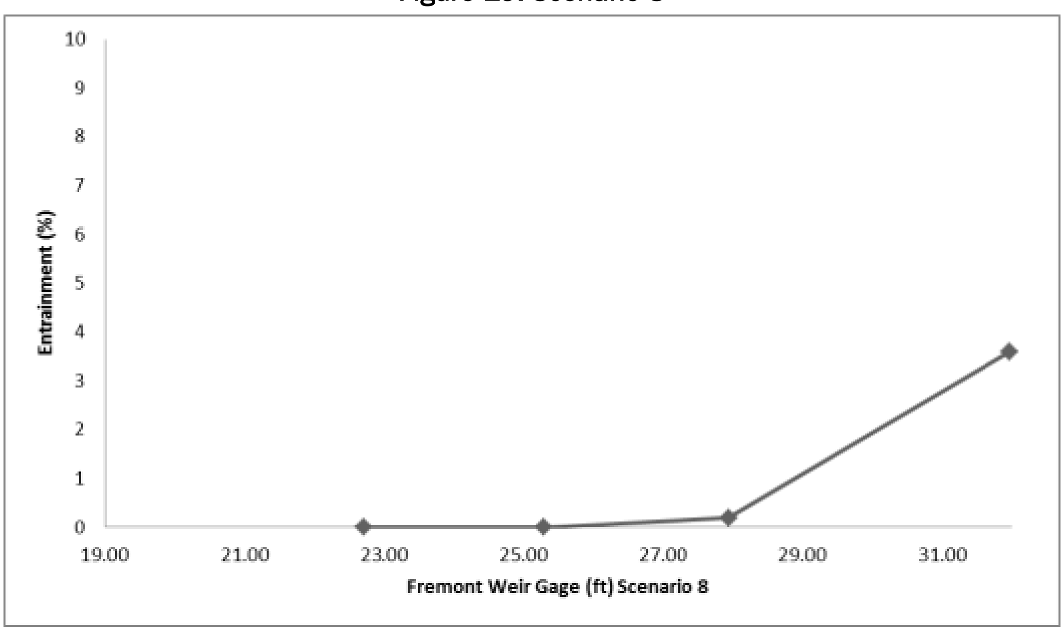
Scenario 7 (Figure 18) entrains approximately 3 to 4% across a wide range of notch flows but has more variability across flows than other scenarios.

Figure 18. Scenario 7



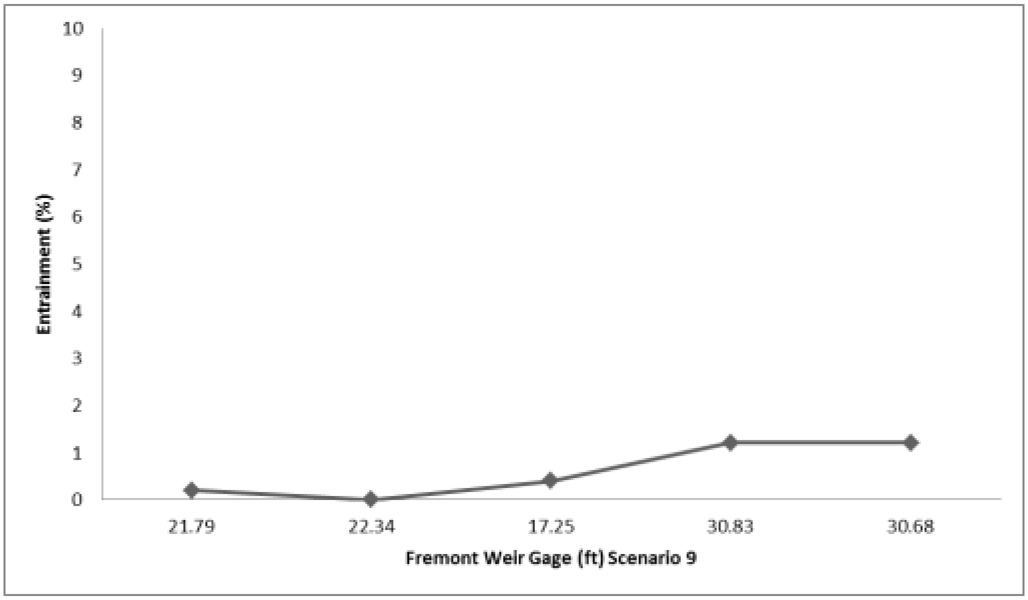
Scenario 8 (Figure 19) entrains approximately 3 to 4% and the entrainment trend suggest that an entrainment plateau has not been reached.

Figure 19. Scenario 8



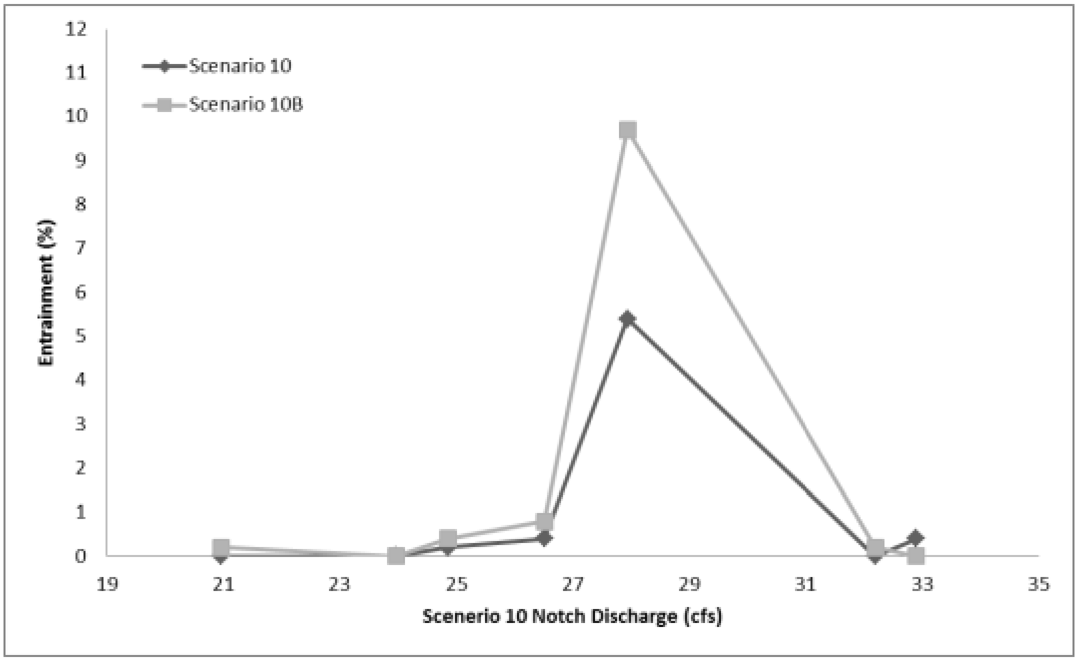
Scenario 9 (Figure 20) entrains approximately 1% and the entrainment trend suggests that an entrainment plateau has been reached. The flow through the notches and estimated entrainment were summed for the combined west and east structures.

Figure 20. Scenario 9



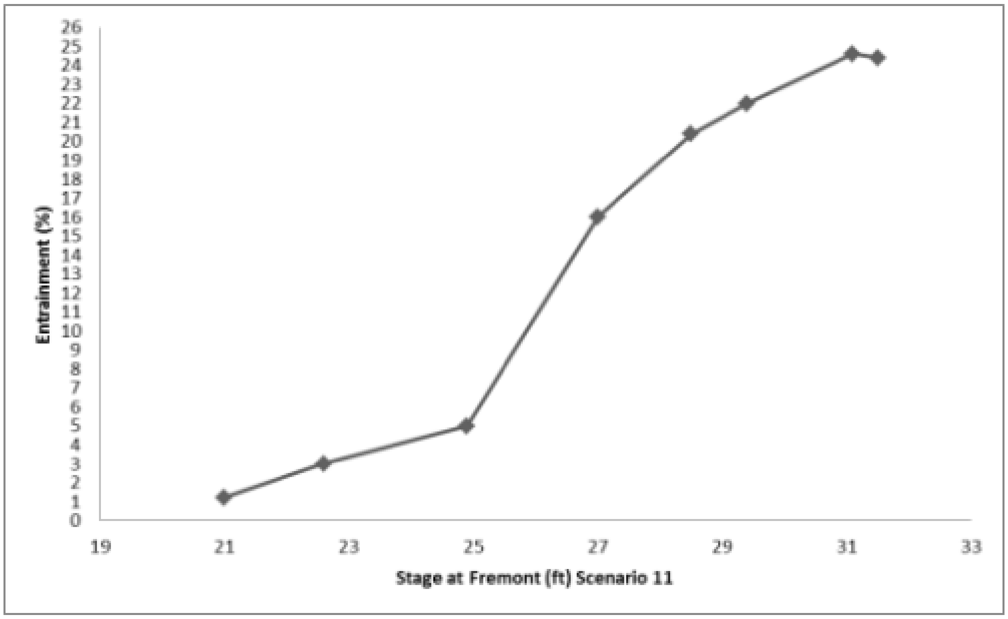
Scenarios 10 and 10B (Figure 21) represent a different notch design on comparison to the other designs. Flows from 37.5 cfs to 3648 cfs (499, 1363, 2098, 2521, 3358, 3402, 3648 cfs) were run incrementally for both Scenarios 10 and 10B covering the range of flows dictated by the rating curve. For both scenarios a flow of 3402 cfs maximized entrainment. All other flows entrained less than 1% of fish. This is likely related to the complicated bank and bathymetry at this location and a recirculation zone that is established in the bend. Please note that there were errors in the notch invert elevations in the original CAD files for Scenario 10 and 10B that were correct in Alterative runs (see Appendix 1).

Figure 21. Scenario 10 and 10B



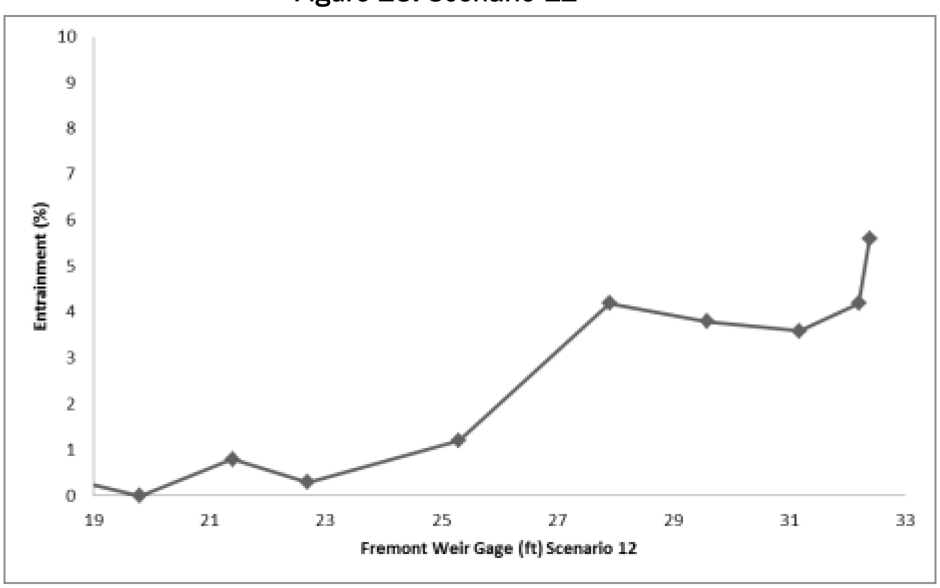
Scenario 11(Figure 22) shows a strong increase in entrainment rates with notch flow and even at the midpoint of flow of 6000 cfs is entraining approximately 15% of the fish and reaching a maximum of approximately 24% at 12000 cfs. Scenarios 11 and 12 are located deeper into the bend than other west scenarios and have a different design lacking a two-step weir and instead relying on a single invert elevation. The width of the structure is wide (220 ft) and it attracts a large cross section of streamlines from the river.

Figure 22. Scenario 11



Scenario 12 (Figure 23) entrains approximately 5% of the fish. The trend suggests a plateau is reached at around 3000 cfs but with an increase suggested at higher stages. This upward trend is likely within the uncertainty of the model.

Figure 23. Scenario 12



We also plot all scenarios on one graph (Figure 24) and provide the plotting data in Table 2. Across all scenarios several trends are suggested.

From stages of 23 to 29 ft there is little meaningful difference in entrainment considering the uncertainty of the point estimates (approximately 3%). Beyond 28 ft there is a decline in entrainment performance for most scenarios with only Scenario 11 clearly deviating from this observation. The decline in entrainment coincides with the approximate elevation of the land surface between the river and the Fremont Weir suggesting a sudden hydrodynamic change that decreases the notch performance. Scenarios 1, 2 and 11 all perform well at stages of approximately 24 to 27 feet with elevated entrainment rates compared to the other scenarios.

Figure 24. Stage at Ferment weir gage and point estimates of entrainment for all ELAM scenarios.

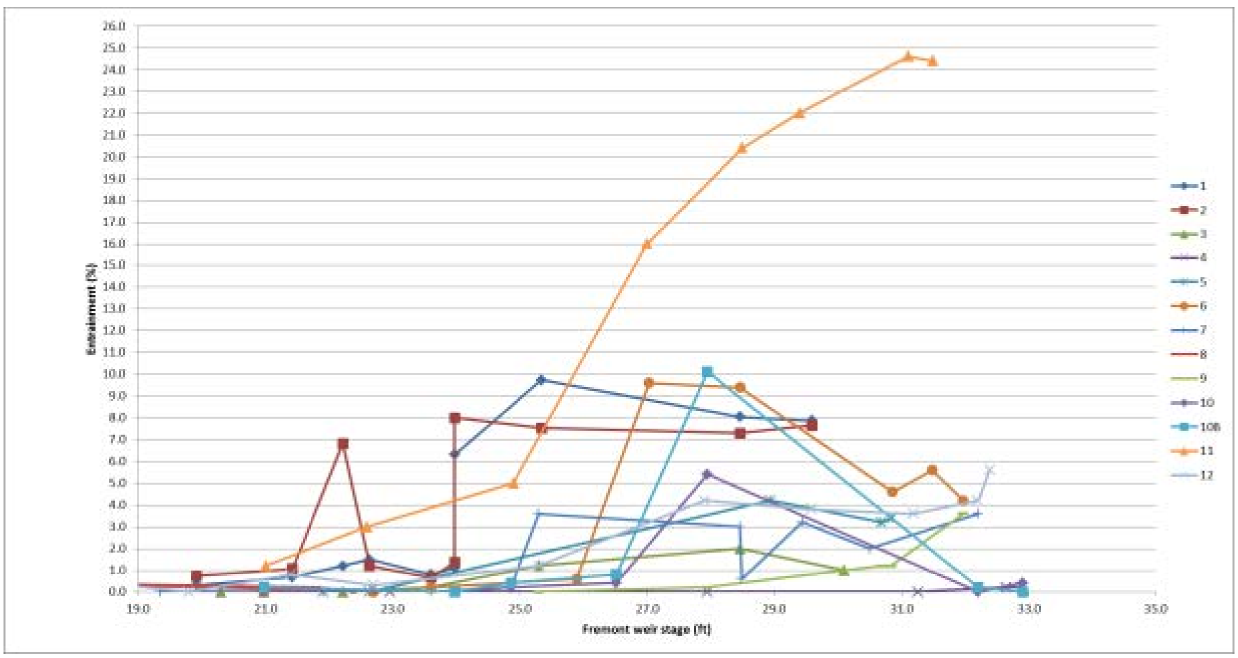
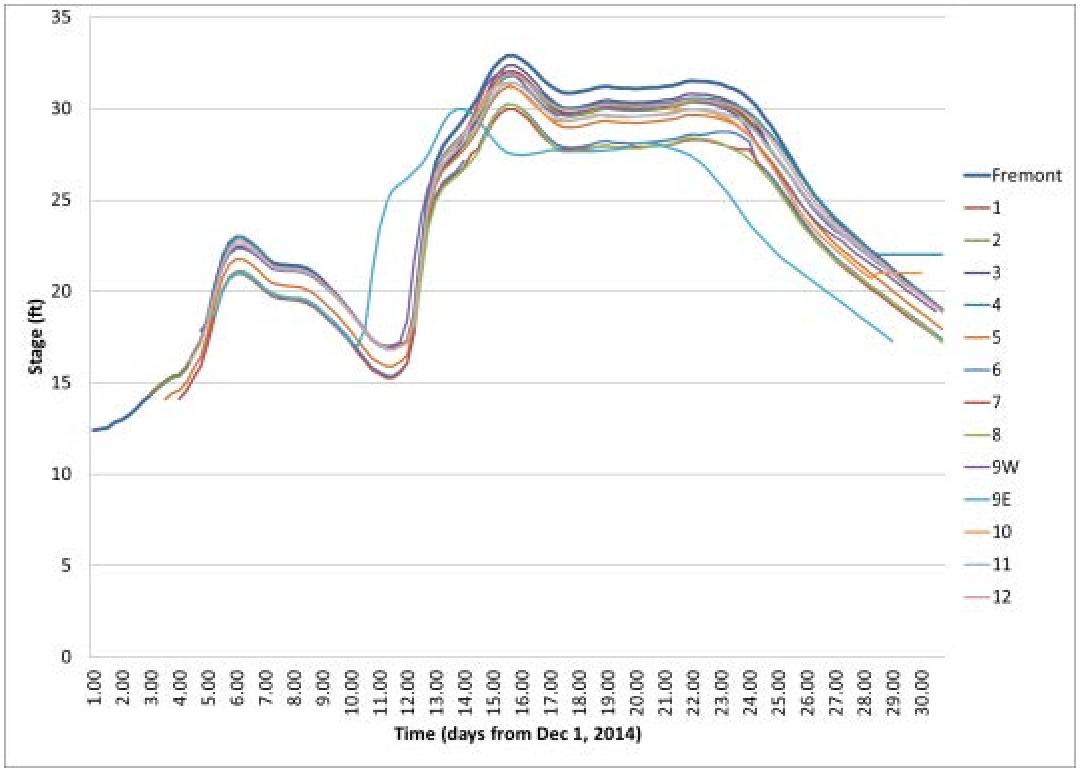


Table 2. Stage at Fremont and point estimates of entrainment for all ELAM scenarios.

Scenario	Fremint stage (ft)	Entrainment (%)	Scenario	Fremont stage (ft)	Entrainment (%)	Scenario	Fremont stage (ft)	Entrainment (%)	Scenario	Fremont stage (ft)	Entrainment (%)
1	19.9	0.3	4	23.0	0.0	8	22.7	0.0	11	21.0	1.2
1	21.4	0.7	4	27.9	0.0	8	17.3	0.4	11	22.6	3.0
1	22.2	1.2	4	31.3	0.0	8	21.8	0.2	11	24.9	5.0
1	22.6	1.5	4	32.6	0.2	8	22.3	0.0	11	27.0	16.0
1	23.6	0.8	4	32.9	0.2	9	25.3	0.0	11	28.5	20.4
1	24.0	1.1	5	21.9	0.0	9	27.9	0.2	11	29.4	22.0
1	24.0	6.3	5	22.6	0.0	9	30.7	1.2	11	31.1	24.6
1	25.3	9.7	5	28.9	4.2	9	30.8	1.2	11	31.5	24.4
1	28.5	8.0	5	30.7	3.2	9	32.0	3.6	12	17.8	0.6
1	29.6	7.9	5	30.9	3.4	10	21.0	0.0	12	19.8	0.0
2	19.9	0.7	6	21.0	0.0	10	24.0	0.0	12	21.4	0.8
2	21.4	1.1	6	22.7	0.0	10	24.9	0.2	12	22.7	0.3
2	22.2	6.8	6	23.6	0.2	10	26.5	0.4	12	25.3	1.2
2	22.6	1.2	6	25.9	0.6	10	27.9	5.4	12	27.9	4.2
2	23.6	0.7	6	27.0	9.6	10	32.2	0.0	12	29.6	3.8
2	24.0	1.4	6	28.5	9.4	10	32.9	0.4	12	31.2	3.6
2	24.0	8.0	6	30.9	4.6	10B	21.0	0.2	12	32.2	4.2
2	25.3	7.5	6	31.5	5.6	10B	24.0	0.0	12	32.4	5.6
2	28.5	7.3	6	32.0	4.2	10B	24.9	0.4			
2	29.6	7.6	7	19.3	0.0	10B	26.5	0.8			
3	20.3	0.0	7	23.6	0.0	10B	27.9	10.1			
3	21.0	0.0	7	24.9	0.2	10B	32.2	0.2			
3	22.2	0.0	7	25.3	3.6	10B	32.9	0.0			
3	23.6	0.2	7	28.5	3.0						
3	25.3	1.2	7	28.5	0.6						
3	28.5	2.0	7	29.4	3.2						
3	30.1	1.0	7	30.5	2.0						
			7	32.2	3.6						

Finally, we plot the modeled stage at Fremont weir and compared it to the modeled stage at each notch across the 12 scenarios for the month of December 2014 (Figure 25). The trend in stage highlights how the gage at Fremont weir, located upstream of the proposed scenarios, is the highest elevation as expected as the distance downstream increases the estimated river stage at the notch also decreases as is expected.

Figure 25. Modeled stage at Fremont Weir compared to stage at each notch entrance in ft, NAVD88.



6 Discussion

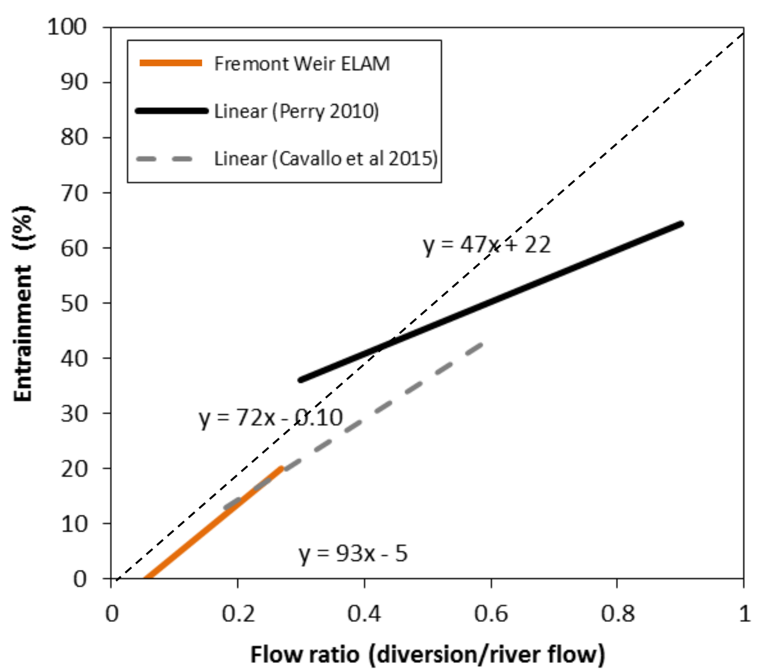
The ELAM was calibrated using fish telemetry data collected in 2015 (Steel et al. 2017) and the CFD simulations (Lai 2016). Once complete, additional CFD runs were made for proposed notches that represented different locations and notch designs (Lai 2017).

The broad pattern of entrainment across all scenarios finds that entrainments estimates vary from a low of approximately 1% to a high of approximately 25%. Ratio of entrainment flow to river flow correspondingly was 2 to 27%. These numbers broadly agree with several studies completed at the Georgianna Slough junction with the Sacramento River. Perry et al. (2014) measured the percentage of fish in 2011 entering Georgianna Slough, which ranged from 1 to 30% with 20 to 30% entering when a non-physical barrier was not operating. The flow split between Georgianna Slough and the Sacramento River was approximately 20% during the study period. Entrainment into Georgianna Slough is strongly dependent on tides and flows. The 2011 year was dominated by high non-reversing flows, conditions under which entrainment probabilities decline dramatically (Perry et al. 2015). Perry et al. (2015) summarized data from a wide range of sources and estimated an entrainment probability from negative to approximately 55% across a number of low flow years. The mean flow ratio between Georgianna Slough and the Sacramento River was 22% with a low of 15 and a high of -17% (more water going down Georgianna Slough than the Sacramento River). Perry (2010) found mean daily flow ratios between Georgianna Slough and the Sacramento River from 2007 to 2009 varied from approximately 30% to 80% and entrainment probabilities 30 to 55%. Finally, Cavallo et al. (2015) summarized data from Sacramento River diversions (Delta Cross Channel, Georgianna Slough, Head of Old River, Sutter Slough, Turner Cut) and concluded entrainment rates varied from 10% to 60% with diversion ratios of approximately 18% to 60%.

We plotted summary data from Perry (2010) and Cavallo et al. (2015) with the ELAM entrainment estimates to contextualize our findings (Figure 26). The data suggest that our entrainment estimates trend well with measured entrainment values within the Sacramento River. However, the diversion ratios proposed at the Fremont Weir notch are generally less than the reported data. In addition the slope relating river diversion ratio to entrainment differs with the ELAM estimates being the most sensitive to river diversion ratio. However, the entrainment estimates we developed overlap suggesting that the ELAM entrainment estimates are reasonable.

The Fremont Weir notch scenarios differ from Georgianna Slough in important ways. First, the proportion of water entrained varies from approximately 1% (Scenario 4) to 27% (Scenario 11). Only Scenario 11 approaches the ratios of flow diverted at Georgianna Slough. The remainder is considerably less. Georgianna Slough is also tidal and the reach has lower current velocities than the Fremont Weir reach which is often around 0.75 m/s. This suggests the exposure time of a fish to the diversion point is less in the Fremont Weir. Finally, cross channel distributions of fish in the Fremont Weir reach and the nearby USACE test reach at river mile 85.6 and 43.7 are relatively insensitive to discharge (Sandstrom et al. 2013, Singer et al. in review, Steel et al. 2017, Woods et al. in review) with most fish tending toward center channel. In comparison, cross channel distributions at Georgianna Slough vary with discharge and stage. Entrainment at any of the Fremont Weir notches may not be as dynamic or of similar magnitude as it is to Georgianna Slough.

Figure 26. Plot of ELAM estimates with comparable estimates from the Sacramento River. Cavallo et al (2015) line estimated by pulling values from graph and thus is an approximation. 1:1 line denotes when entrainment is proportional to entrainment flow.



The difference in slope between the ELAM and the Georgianna Slough may also be partially explained through differences in the river environment. The Fremont Weir is strongly advective and fish movement though this reach reflects that. In comparison, the tidal junction at Georgianna Slough induces upstream movement, station holding along the bank and in general more complicated swim paths. Of the studies, Perry et al. (2014) is the most comparable to the Fremont Weir because reversing flows were rare. The ratio between Georgianna Slough and the Sacramento River was approximately 16% and entrainment was approximately 22% when a non-physical barrier was not operating. This compares with a ratio of 27% flow for 25% entrainment for Scenario 11 (the largest notch evaluated).

We may underestimate entrainment for Scenarios 1, 2, 3, 4, 9, 11, and 12, all located in the western portion of the notch. This is because the spatial distributions of the modeled fish deviate from the measured distribution with the measured fish having a larger outside bend density. Broadly, the kernel density estimates overlap and agree but entrainment is sensitive to lateral position in the channel. The difference is likely due to not representing secondary circulations in the 2D hydraulic model. We believe this is acceptable because of the following reasons. First, developing 3D time varying RANS (Reynolds-averaged Navier–Stokes) simulations for all 12 alternatives was infeasible. Working in 2D allowed all the spatial domains to be represented. Future design work (as opposed to planning work) may need to consider 3D simulations. Second, the bias introduced by the lateral distribution is equal across all alternatives. Third, the ELAM estimates are comparable to other entrainment estimates from the Sacramento River suggesting whatever potential underestimation we report is likely within the range of variation we expect to see within existing measured entrainment data sets.

There are some additional caveats to this study as we presented model results that will apply to future engineering design and analysis.

6.1 Accuracy and precision in planning studies

This study has provided entrainment estimates for a range of scenarios. The results should be viewed cautiously for several reasons. First, there is no fish entrainment data for any notch that was modeled. We simply calibrated to existing conditions (base scenario) and extended that calibration to the 12 notch scenarios. Each notch scenario reported has an error bar associated with it which captures the variability of the entrainment as modified by varying ELAM boundary conditions slightly. Thus each scenario entrainment estimate is an ensemble estimate which is considered a best practice for physical system numerical modeling. However, since the real entrainment rate is unknown the raw estimates should not be viewed as absolute numbers. Rather, the entrainment estimates should be used as relative entrainment rates to highlight differences across scenarios. This is consistent with USACE best practice. Future work should include more detailed modeling and after construction measurement of notch performance.

6.2 Behavior

Fish have a near limitless level of behaviors that can be implemented and our representation is inherently limited by incomplete understanding. The behavior quantified in Steel et al. (2017) was simple but undoubtedly other behaviors which might influence movement were occurring but were not measured. In addition, the notch will change the local environment and expose fish to acceleration gradients in excess of what is found in the river. Elevated acceleration gradients generally repel migrating juvenile salmon.

In addition, data and behavior for fry sized salmon are largely unavailable. USACE studies suggest very limited numbers of fry size salmon near banks. Susceptibility of fry size salmon to a notch may be greater than smolts or, if fry size fish are migrating similarly to parr and smolts then entrainment estimates may correspond to results in this study. Finally, hatchery fish were used for calibrating of this study and may not be a surrogate for wild fish.

6.3 Notch flow and design

Across all scenarios larger notch flows entrain greater fish numbers, although not proportionally to the volume through the notch. West located notches entrain more fish than central and east and intakes perform better than shelfs. However, intakes and shelfs both performed poorly, regardless of notch flows, when intake channels were angled from the mainstem.

A primary exception to notch flows being the most important design criteria is demonstrated with Scenario 10B. Scenario 10B was a late modification of Scenario 10 and those modifications improved notch performance.

These findings highlight the importance of hydrodynamics along the upstream bank and angle of the intake off of the Sacramento River for optimizing fish entrainment. Additionally, the substantial biological response resulting from stakeholder-generated scenario design changes suggest this model can further analyze advance optimization exercises and higher-order design drawings.

6.4 Unknown factors that influence entrainment

When a notch is constructed it may closely resemble the scenarios examined in this study or it may deviate. We captured many details of each scenario including structural changes and bankline, bathymetry, and overbank changes. As the design goes forward additional details will be added and these details may begin to deviate from what was analyzed as part of this study.

6.5 2D data in 3D river

Depth information for fish is unavailable. The measured positions therefore are in 2D. Not having depth information induces uncertainty in the measured positions. As fish move deeper, as may occur in the river bend, the estimated path length measured in 2D diverges from the 3D path length. This bias is inherent in the fish position data used for this study.

6.6 Impact of bank structures on secondary circulations

Secondary circulations are one factor driving the lateral distribution of fish in the Sacramento River with the likely result of shifting fish positions toward the outside bank. When one of the scenarios is implemented and constructed, we would expect that the existing secondary circulation patterns in the vicinity of the notch will change. For example, bend way weirs are put along the outside bends of river expressly to disrupt secondary circulations. The end result may be that the constructed structure diminishes the tendency of to skew lateral distributions to the outside bend.

6.7 Low calibration flow

The 2015 fish telemetry work was completed at a low stage of approximately 14 ft. Additional data was collected in 2016 at much higher flows and as the design process moves forward using a wider range of fish data across more flows would help strengthen the modeling effort and support project completion more fully.

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8 Appendix 1: EIS/EIR Alternatives 1 through 6 Entrainment Estimates

8.1 Reason for Addendum

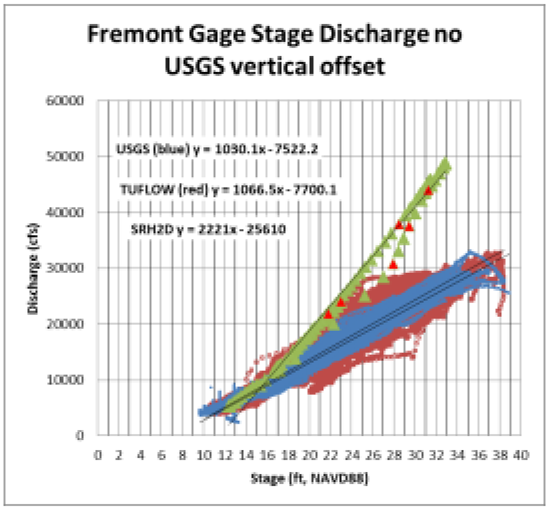
The EIS/EIR alternatives have been under refinement for the duration of the entrainment modeling with six near final concepts provided to the entrainment modeling team in early June 2017. This is long after the previous 12 scenarios had been run and summarized. The project required some additional simulations of the EIS/EIR alternatives to better capture the anticipated alternative differences.

Late input from USGS (mid-June 2017) noted that the 2D model (Lai 2016) likely was putting more water through the Sacramento River than is expected (Figure 27) while accurately representing the stage at Fremont Weir gage. The explanation for this is in Lai (2016) and simply reflects the unknown inflow locations of water flowing from the Sutter Bypass into the Sacramento River.

Reducing the flow in the model to match USGS provided suggestions will influence entrainment estimates because a larger portion of river water will be diverted at a notch for a given stage. The influence will be greater at higher stages. Therefore we reran the EIS/EIR Alternatives using the new flow information and by adjusting the boundary conditions as follows:

We adjusted the boundary conditions as follows. The difference in discharges between the old way and the new USGS way, i.e., Q_at_Fremont_OldWay-Q_at_Fremont_USGS, is added to Sacramento Slough Karnak first (up to 50 cms), and then to the Feather River confluence with the Sacramento River with the remaining flow. This way, the total discharge matches the 2014-2015 recorded discharge hydrograph at the Verona Station and the flows passing the Fremont Weir gage match USGS estimates.

Figure 27. USGS and DWR rating curves and the SRH2D output used for the entrainment estimates for the original 12 scenarios.



To evaluate how this impacts the overall conclusions of the analysis, we developed 36 separate simulations with 6 stages and flow based on the USGS rating curve for the Fremont Weir site. We decided to enhance evaluation across the EIS/EIR alternatives by running the exact same hydro for each alternative (Table 3). Some of these stages and alternatives are represented in the original 12 ELAM scenario analyses but with different flows and sometimes different geometries.

Table 3. New stages and flows used for the EIS/EIR Alternatives.

Stage (ft NAVD88) at Gage	Original Q (cfs) at gage	USGS rating curve Q (cfs)	Upper bound of data envelope (est)	Lower bound of data envelope (est)
21.79	21888	14925	14925	10546
22.99	24074	16161	16161	12800
27.94	30809	21261	27583	19300
24.5	28805	17717	27900	14364
29.44	37635	22806	27915	20200
31.22	45018	24640	28222	22546

With the new boundary conditions applied we found that the model predicted stage at the Fremont Gage (4th column in the Table 3) does not match the “nominal” stage in the first column. The model predicted stages are 1.5 to 2.4 ft lower than the nominal stage. We have matched the recorded stage and discharge at the Verona Station; at the same time we used the discharge through the Fremont Gage according to the USGS rating curve (Table 4). This mismatch suggests something else is going on. We conjecture that the mismatch may be caused by: (1) 2015 flow was towards the high end of the flows through the Fremont Gage area but we used the “average” flow according to the USGS rating curve, and/or, (2) unaccounted flow distribution along the Sutter Bypass flows back to the Sacramento River. Despite the mismatch, this set of new data should provide a new set of possible conditions occurring at the Fremont Weir site that may be used to address the variability issue.

Table 4. Stage and flow used for EIS/EIR Alternatives 1 through 6.

Stage(ft) at Fremont	Q(cms) at Fremont from USGS	Q(cms) at Fremont based on Old Way	Stage(ft) predicted by the model at Fremont
21.79	14952	16063	20.23
22.99	16161	17924	21.16
24.5	17717	20066	22.32
27.94	21261	26601	25.54
29.44	22806	30944	27
31.22	24640	42166	28.83

All entrainment simulations were run using the same boundary conditions as the twelve ELAM scenarios. No ensembles were developed due to time constraints. We anticipate developing the ensembles at a later date.

8.2 Results

Results are shown graphically (Figure 28) and with a Table (Table 5).

Figure 28. Entrainment estimates across flows and stage referenced to Fremont Weir gage.

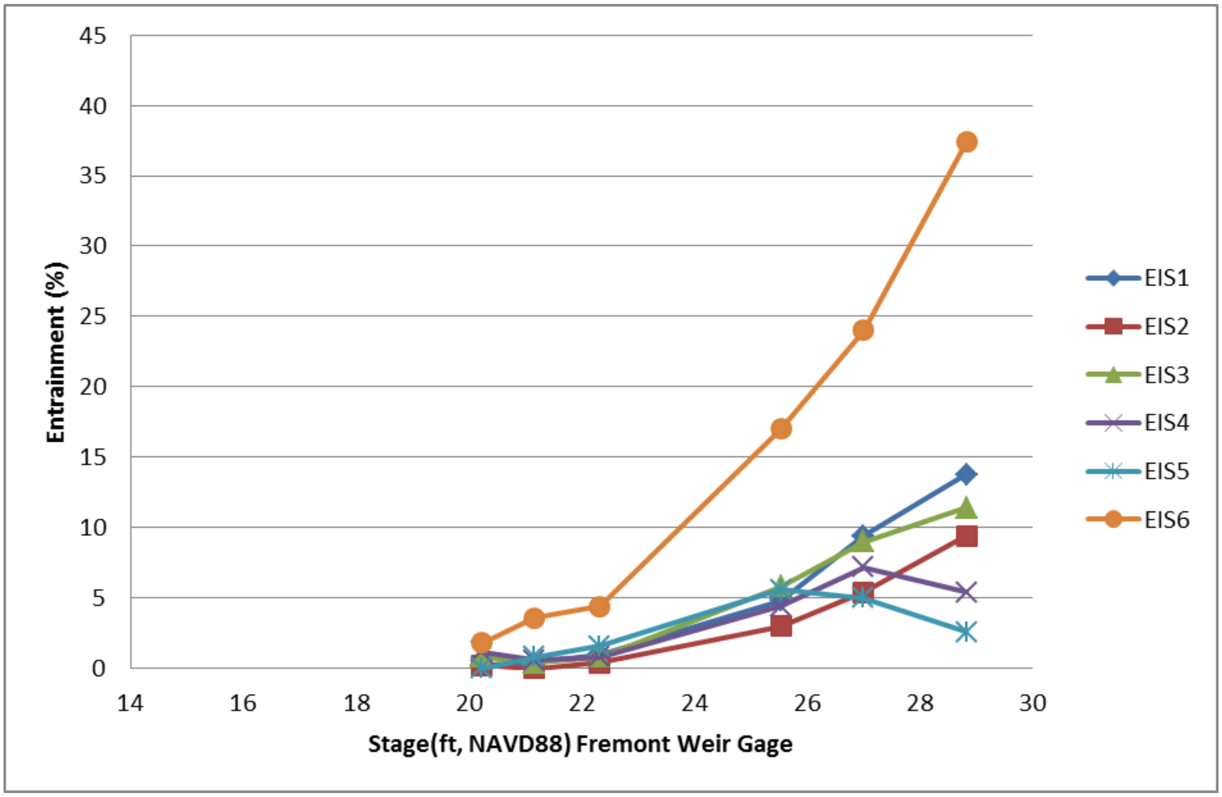


Table 5 .Entrainment estimates across flows and stage referenced to Fremont Weir gage.

Statge (ft) Fremont	Q (cfs) Fremont	EIS/EIR Alt 1	EIS/EIR Alt 2	EIS/EIR Alt 3	EIS/EIR Alt 4	EIS/EIR Alt 5	EIS/EIR Alt 6
20.23	14952	0.2	0.2	0.8	1.2	0	1.8
21.16	16161	0.4	0	0.4	0.6	0.8	3.6
22.32	17717	1	0.4	0.8	0.8	1.6	4.4
25.54	21261	4.8	3	5.8	4.4	5.6	17
27	22806	9.4	5.4	9	7.2	5	24
28.83	24640	13.8	9.4	11.4	5.4	2.6	37.4

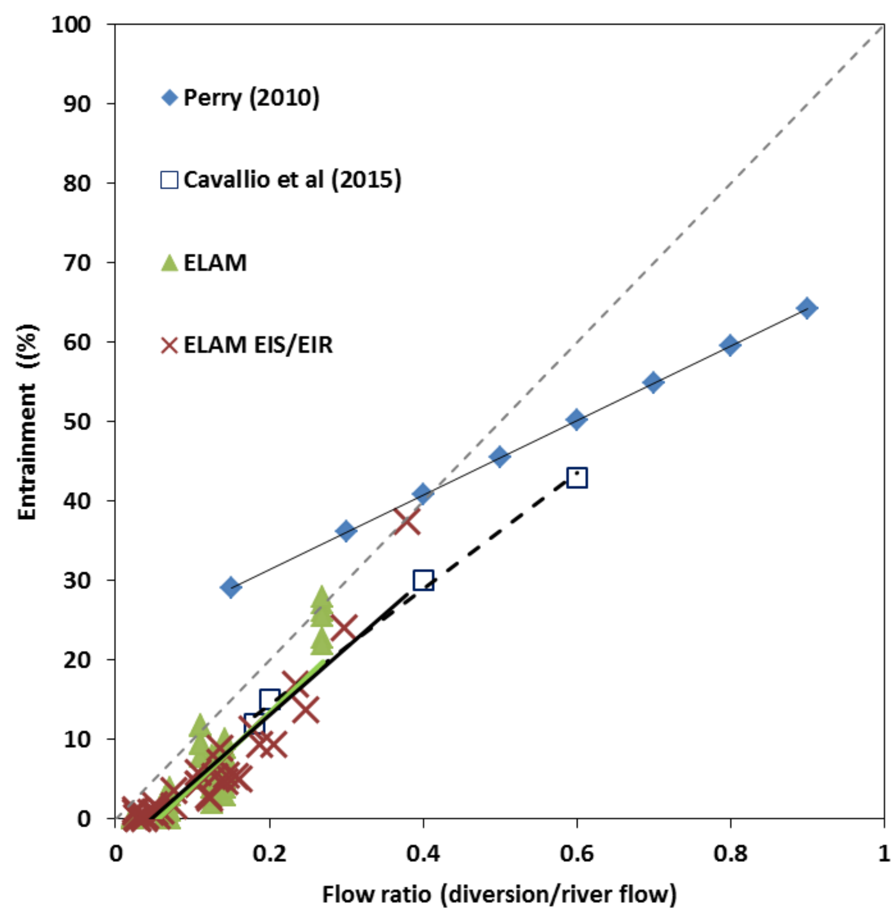
As expected, the lower flows (Column 3, Table 3) compared to the twelve ELAM scenario simulations compared well at the lower stages and flows (20.23 to 25.54 ft). At the higher flows and stages of 27 and 28.83 ft, the EIS/EIR tended to be higher. This is because the ratio of flow between the river and the notch is greater for the EIS/EIR alternatives than for the 12 ELAM scenarios.

Broadly, higher stages and entraining flows result in greater entrainment and entrainment is less than 5% for all alternatives at stages below 25.5 ft (NAVD88) at Fremont Weir gage.

One departure between the twelve ELAM scenarios and the EIS/EIR alternatives is EIS/EIR Alternative 1. EIS/EIR Alternative 1 is similar to Scenario 7. Both are located at the east end of the Fremont Weir and have similar flows with a nominal maximum of 6,000 cfs. However, EIS/EIR alternative 1 entrains approximately 14% of the fish at 6000 cfs while ELAM Scenario 7 entrains approximately 4% of the fish. The differences are attributable to dimensions of the EIS/EIR structure (Table 4).

We checked the entrainment estimates against report entrainments for Sacramento River salmon as a validation of our results (Figure 29). The new EIS/EIR Alternatives 1 through 6 entrainment estimates compare favorably with the twelve ELAM scenarios and also are reasonable when compared to actual entrainment rates in the Sacramento River.

Figure 29. Validation plot of estimated entrainments for the EIS/EIR Alternatives. Grey dashed line is the 1:1 line where entrainment is proportional to flow ratio.



8.3 Conclusions

1. The recommendation to use the entrainment estimates as relative indicators of notch performance when compared across all notches still stands. However, the favorable comparison with measured data comparing entrainment rates elsewhere in the Sacramento is encouraging and adds credibility to the analysis.
2. Broadly, higher stages and entraining flows result in greater entrainment and entrainment is less than 5% for all alternatives at stages below 25.5 ft (NAVD88) at Fremont Weir gage.
3. One departure between the twelve ELAM scenarios and the EIS/EIR alternatives is EIS/EIR Alternative 1. EIS/EIR Alternative 1 is similar to Scenario 7. Both are located at the east end of the Fremont Weir and have similar flows with a nominal maximum of 6,000 cfs. However, EIS/EIR 1 entrains approximately 14% of the fish at 6000 cfs while ELAM Scenario 7 entrains approximately 4%

of the fish. The differences are attributable to dimensions of the EIS/EIR structure (Table 6).

Table 6. Comparison of EIS/EIR Alternative 1 and ELAM Scenario 7 highlighted in green.

ELAM EIR/EIS Alternative Information								
EIR/S Alt	Location	Shelf/ Intake	Max Flow	Main Channel-Gate 1 (Invert) Ft.	Main Channel-Gate 1 (Width) Ft.	Elevated Channel Gates 2&3 (Invert) Ft.	Elevated Channel Gates 2 & 3 (Width) Ft.	Full Intake (Btm Width) Ft.
1	East	Intake	6,000	14	34	18	27	98
2	Central	Intake	6,000	14.8	40	18.8	27	104
3	West	Intake	6,000	16.1	40	20.1	27	104
4	West	Intake	3,000	16.1	40	20.1	27	104
5	Central	Intake	3,000	14 (A), 17 (B)	10x3 (A), 10x3 (B)	20 [C], 23 [D]	10x10 [C], 10X11 [D]	75 [A&B], 128 [C], 140 [D]
6	West	Intake	12,000	16.1	40 x 5	n/a	n/a	220
ELAM Original Configuration Information								
Config #	Location	Shelf/ Intake	Max Flow	Main Channel-Gate 1 (Invert) Ft.	Main Channel-Gate 1 (Width) Ft.	Elevated Channel Gates 2&3 (Invert) Ft.	Elevated Channel Gates 2 & 3 (Width) Ft.	Full Intake (Btm Width) Ft.
1	West	Shelf	6,000	14	36	20	23	82
2	West	Intake	6,000	14	36	20	23	82
3	West	Shelf	3,000	17	24	23	13	50
4	West	Shelf	1,000	22	15	n/a	n/a	15
5	Central	Shelf	6,000	14	36	20	23	82
6	East	Shelf	6,000	14	36	20	23	82
7	East	Intake	6,000	14	36	20	23	82
8	East	Shelf	3,000	17	24	23	13	50
9	Est&Wst	Shelves	3,000 EA	17	24	23	13	50
10	Central	Intake	3,000	14 (A), 17 (B)	10x3 (A), 10x3 (B)	18 [C], 21 [D]	10x10 [C], 10X11 [D]	75 [A&B], 128 [C], 140 [D]
11	West	Intake	12,000	16.1	40 x 5	n/a	n/a	220
12	West	Intake	6,000	16.1	40	20.1	27	104

EIS/EIR Alternative 1 is a good example of how using the ELAM approach is useful for project planning and alternative comparisons because the workflow allows preliminary designs to be represented with high fidelity. This assists with maintaining as much of the project details during the planning and ultimately designs phases of the project. The modification of ELAM scenario 7 into EIS/EIR Alternative 1 suggests that the ELAM workflow including the computer representation and subsequent flow field and fish modeling may ultimately result in a cost effective structure.

Finally, this workflow resulted in valuable and accurate spatial domains representing the bathymetry, topography, and structure suitable for subsequent planning and design including finite element modeling and computational fluid dynamics in two and three dimensions.

4. The EIS/EIR Alternatives were run at similar stages but lower flows than the ELAM Scenarios because of recent input from USGS and the stage discharge relationship in the Fremont Weir reach. The analyses of the ELAM 12 scenarios were completed with accurate stage estimates but elevated discharge estimates (Figure 23).

The effect of this is that there are higher river velocities in the model which translates into higher speed over ground estimates for simulated fish. In addition, the ratio of diverted flow to river flow is smaller suggesting that we may have underestimated the proportion of fish entrained. However, the new alternative results suggest that the higher flows did not grossly underestimate entrainment.