INTEGRATION OF 2-D NUMERICAL AND PHYSICAL MODELING AT THE PROPOSED RED BLUFF FISH SCREEN AND PUMPING PLANT

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Abstract: Fish passage of endangered salmonids and green sturgeon on the Sacramento River is impeded by the Red Bluff Diversion Dam when the gates are down. A pumping plant facility with a fish screen will be built to allow for safe fish passage year round while also meeting current and future irrigation deliveries to the canal service area. Identifying hydraulic and sediment transport characteristics in the Sacramento River and along the fish screen was vital to the design. Both numerical and physical models were used to analyze these conditions because each model has its own set of uses and limitations. The concurrent use of the models provided a better understanding of the proposed facility.

A physical model and two-dimensional (2-D) numerical model of the river channel were used to determine anticipated water surface elevations in the river with and without diversion as well as sweeping velocities along the fish screen structure. A 2-D hydraulic numerical model covered approximately five miles of river channel with the fish screen in the river, but did not include the pumping plant forebay geometry. A 1:42 scale physical model included the proposed fish screen and pumping plant forebay, Red Bank Creek, and 2,200 feet of river channel. The numerical model simulated a range of flows (normal and storm conditions) with and without diversion and provided water surface elevation profiles along the fish screen. Water surface elevations from the numerical model compared well with the physical model measurements. The physical model provided detailed sweeping and approach velocities along the fish screen. In addition, the physical model was used to determine baffle settings to provide uniform velocities along the entire fish screen length.

Predictions of sediment deposition and scour patterns along the fish screen were developed from the models. Fine sand was fed into the upstream end of the physical model under a high, steady flow condition to provide a qualitative assessment of deposition zones. However, the physical model had a fixed bed so no scour could occur. A 2-D prototype-scale hydraulic and sediment transport numerical model was used to determine where and what amount of sediment would deposit or erode near the fish screen structure. Unsteady flows of average 2-year, 10-year, and peak of record hydrographs were simulated in the numerical model. Because of time and physical constraints, it was not possible to simulate the same hydrographs in the physical model, but sediment was observed moving through the fish screen and baffles and depositing in the pumping plant forebay. An additional 2-D numerical sediment and hydraulic model was developed of the physical model for verification purposes. The ability to use the collaborative results from the physical and 2-D numerical models allowed many design questions to be answered more accurately and thoroughly than using only one model.

INTRODUCTION

The Red Bluff Pumping Plant is designed to replace the Red Bluff Diversion Dam (RBDD) which is located on the Sacramento River, near the city of Red Bluff in north central California. The project provides water to the west side of the Sacramento River valley for irrigation purposes. Ineffective fish passage at RBDD has been identified as a contributing factor to the decline of the anadromous fishery resource in the upper Sacramento River basin.

The proposed 2,500 ft^3/sec capacity pumping plant and 1,100-foot-long fish screen will be located on the west bank of the Sacramento River approximately 1,500 feet upstream from the existing Red Bluff Diversion Dam. Multiple design questions were identified for the proposed fish screen. Models were utilized to evaluate the following flow and sediment transport issues:

- Future water surface profiles through the reach based on a range of river and diversion flows
- Future erosion and depositional patterns in the river and along the proposed fish screen during and after flood events
- Streamwise velocities at the screen locations
- Screen flow conditions and associated velocity distribution based on a range of river and diversion flows
- Identification of methods to improve screen performance and forebay flow conditions

The following models were used in the analysis:

- Numerical: Sedimentation and River Hydraulics Two-dimensional (SRH-2D) Hydraulic Model
- Numerical: SRH-2D Hydraulic and Sediment Transport Model
- Physical: Physical Hydraulic Model Study (1:42 scale)
- Numerical: SRH-2D Hydraulic and Sediment Transport Model of the Physical Model (1:42 scale)

METHODS

2-D Hydraulic Model: A 2-D numerical model was developed to determine the water surface elevations along the proposed fish screen with and without a diversion of 2,500 ft^3/sec (Reclamation 2009a). The numerical model utilized for this assessment was SRH-2D (Lai 2010), a 2-D depth-averaged hydraulic model specifically focused on the flow hydraulics of river systems. Input to the model includes: a topographic mesh, incoming discharge, flow roughness, and a downstream boundary condition for the water surface elevation. Bathymetric data was collected above and below RBDD on August 19 and 20, 2008. Additional bathymetric data was collected near the proposed fish screen on November 25, 2008. This data was used below the water line in combination with USGS 10 meter DEM points above the water line to create a Triangulated Irregular Network (TIN) terrain model (see Figure 1).

A mesh was generated in this area using SMS (Surface-Water Modeling System V. 10, Aquaveo) software. Approximately 5 miles of river channel upstream of RBDD was modeled. A quadrilateral mesh was used within the River, East Sand Slough, and Red Bank Creek. A triangular mesh was used outside of the main flow paths. The mesh near the proposed fish screen area was approximately twice as dense as the surrounding channel to provide more detailed results. Mesh elements were assigned elevations from the TIN to represent the terrain. The fish screen structure was included in the initial model geometry. Elevations along the fish screen were adjusted to 235.83 feet (NAVD 88) to account for the fish screen sill elevation; the fish screen structure is approximately 31.5 feet high. An infinitely high no-slip wall boundary was extended vertically along the fish screen. This scenario did not allow flow into the fish screen but models the obstruction in the river. The 2-D model could not be directly calibrated because it represented proposed conditions; therefore the 2-D model was verified (by adjusting flow roughness) using a one-dimensional (1-D) HEC-RAS model (Reclamation 2009b) that had been validated against the current conditions. After validation, the 1-D model was adjusted to account for diversion through the fish screen and the water surface elevations from this scenario were used to verify the 2-D model. Results from the 1-D HEC-RAS model were used to establish a downstream water surface elevation boundary condition for the 2-D model. Inflows to the 2-D model ranged from between 2,000 to 141,000 ft^3/sec.

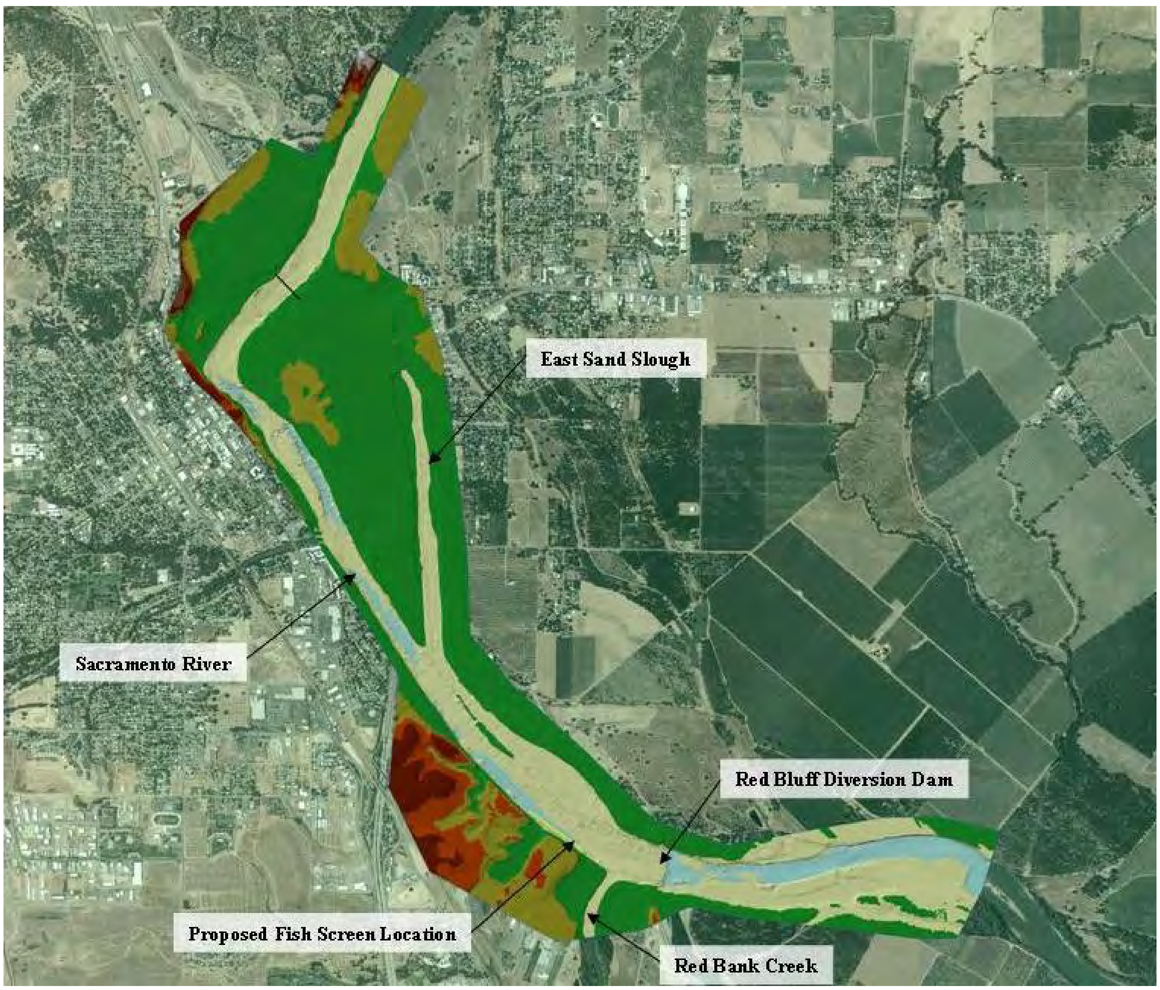

Figure 1. TIN developed from bathymetric survey and USGS DEM elevation points.

2-D Hydraulic and Sediment Transport Model: A 2-D numerical hydraulic and sediment transport model was created for the Sacramento River near the proposed fish screen using the same general model extent as that of the hydraulic model (Reclamation 2009c). The objectives were to determine the amount of deposition or erosion expected to occur along the proposed fish screen during and after flood events. Input to the model includes; a topographic mesh, bed material gradation, inflow discharge and sediment load, channel roughness, and a downstream boundary condition for the water surface elevation.

The 2-D hydraulic mesh was altered using SMS to reduce the computational time requirements of the unsteady sediment transport calculations via a reduction in mesh elements. The number of mesh elements was reduced from 24,000 to approximately 7,700. The majority of the changes occurred in the upstream portion of the model to minimize any changes near the fish screen. In addition, all out of bank triangular mesh cells were changed to quadrilateral elements in the area near the proposed fish screen. The mesh elements upstream of the forebay were removed because flow was not out of bank in this area. The 2-D hydraulic mesh and modified 2-D hydraulic and sediment transport mesh are shown in Figure 2.

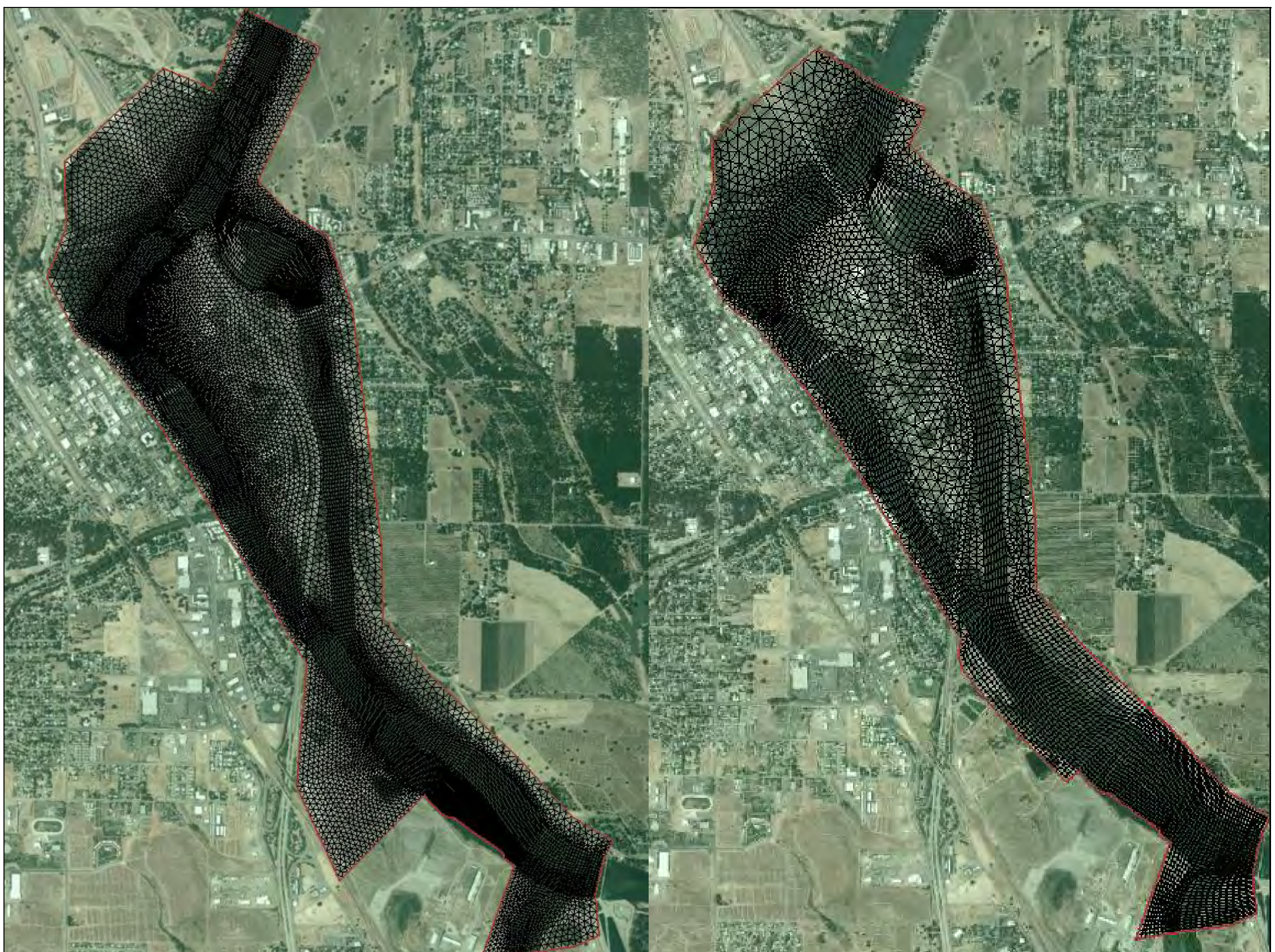

Figure 2a. Mesh used for 2-D hydraulic simulations.	Figure 2b. Modified mesh for hydraulic and sediment transport simulations.

The incoming sediment load was calculated by the model to maintain capacity at the upstream node string. No bed material samples were collected in the project area, so bed material had to be estimated using samples collected outside the project area. A power function was developed that estimates the bed material size as a function of river mile based on the California Department of Water Resources (DWR) 1995 and 1984 data for surface and subsurface material. The proposed fish screen is located at river mile 243.2; the sediment gradation at this location was calculated for the surface and subsurface and applied uniformly to the entire modeling domain. The entire bed was assumed to be alluvium although geotechnical land borings indicated that the Tehama formation (a very dense cemented silty sand) exists approximately 8 feet below the channel. Detailed information on the Tehama formation was not available to allow its inclusion in the model.

Three storm events, 2-yr, 10-yr and peak of record, were simulated in the model. The hydrograph peaks ranged from 77,450 to 186,000 ft^3/sec. The downstream water surface elevation rating curve used in the 2-D hydraulic simulations was also used in the 2-D hydraulic and sediment transport simulations. The hydraulics and sediment model could not be calibrated to field data because it represented proposed field conditions. Instead water surface elevations were compared and validated with the 2-D hydraulics model. In addition, several model parameters, such as sediment input load, could not be calibrated since data sets were not available to determine these parameters.

Physical Hydraulic Model: The physical hydraulic model study documented the hydraulic characteristics and performance of the Red Bluff Pumping Plant’s positive barrier fish screen design. Data were also used to enhance the fish screen performance so that it meets or exceeds performance criteria set forth by the National Marine Fisheries Service (NMFS) and the California Department of Fish and Game (CDFG) that the approach flow velocity perpendicular to the screen face does not exceed 0.33 feet/sec. This criterion is intended to prevent impingement of juvenile salmonids on the screens. Modifications to the fish screen design were made to improve performance with respect to approach and sweeping velocity criteria. The model was also used to qualitatively assess bedload transport along the fish screen structure.

The hydraulic model was constructed to a 1:42 geometric scale using Froude law relationships in a water tight box with dimensions of 44 feet wide, 90 feet long, and 4 feet deep as depicted in Figure 3 (Reclamation 2009d). The model scale was selected to allow the construction of the fish screen and sufficient channel length to accurately reproduce the riverine hydraulics. The model includes the Red Bluff Pumping Plant forebay and fish screen (the model contained all 60 fish screen bays), 3,800 ft of Sacramento River channel and floodplain, and 200 ft of Red Bank Creek and delta.

A fine sand mix was chosen for the model so that bedload would actively transport during the prototype flow of 80,000 ft^3/sec. Fine sand was introduced to the main river channel only and not Red Bank Creek because sediment transport past the screen structure was the primary interest. The physical model had a concrete floor at the original bed elevation and therefore could not provide any information on potential scour related to the hydraulic structures.

Acoustic Doppler velocity measurements could not be made at a prototype distance of 3 inches (1/16 inch model) from the screen face, as required by fish screening evaluation criteria, because of acoustic interference. In addition, shallow depths in the model did not allow the evaluation of vertical velocity distribution for individual screen bays.

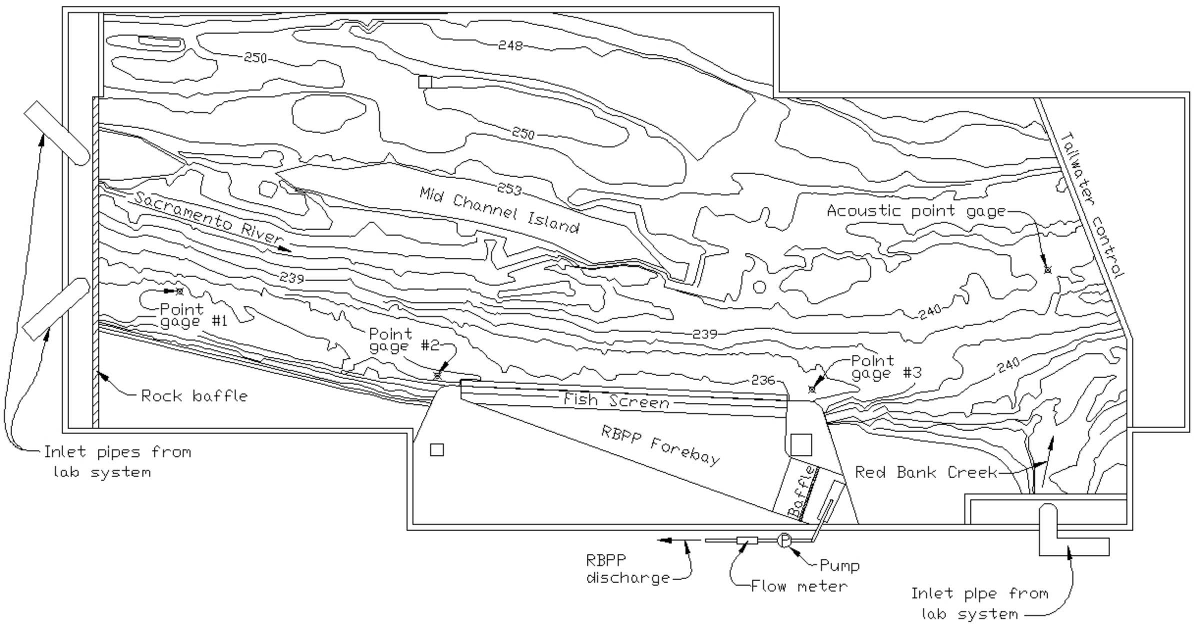

Figure 3. Plan view schematic of the Red Bluff Pumping Plant fish screen hydraulic model.

<u>Numerical Hydraulic Model of the Physical Model</u>: A 2-D hydraulic and sediment transport numerical model was developed to compare with the sedimentation patterns from the 1:42 scale laboratory physical model (Reclamation 2009e). The comparison was used to validate the numerical model being conducted at the prototype scale. This also promoted confidence in the numerical model being used for more rapid assessment of future simulations that would be time consuming and cost prohibitive to do with the physical model.

The AutoCAD contours used for construction of the physical model were used for the creation of a TIN. A computational mesh was constructed using SMS software. The upstream boundary for the SRH-2D model used an inflow discharge of 7 ft^3/sec (80,000 ft^3/sec prototype flow) distributed over the length of the model baffle. The sediment was input over just one of three upstream boundary segments along the right bank to best simulate physical model conditions. The sediment input to the model was a fine sand mix that was added at a rate of 25 pounds/hour (roughly 1,500 pounds total). The numerical model assumed the incoming sediment load was constant where the physical model input the sand in discrete intervals. To represent the physical model having a fixed bed that did not allow for scour, a large size class known to be immobile at the modeled flow was added to the sediment gradation and used to represent the surface bed layer; in essence, armoring the model topography.

RESULTS

Each model provided results that were used to address various design questions. From the 2-D hydraulic model, profiles of water surface elevations from RBDD to upstream of the fish screen were generated. Figure 4 shows the alignment of the profiles. The fish screen structure is located between station 1825 and 2915. The resulting profiles of three scenarios are shown in Figure 5: one profile for 12,600 ft^3/sec flow with no diversion, one profile for 10,000 ft^3/sec flow with no diversion and one profile for a flow of 12,600 ft^3/sec with a 2,500 ft^3/sec diversion.

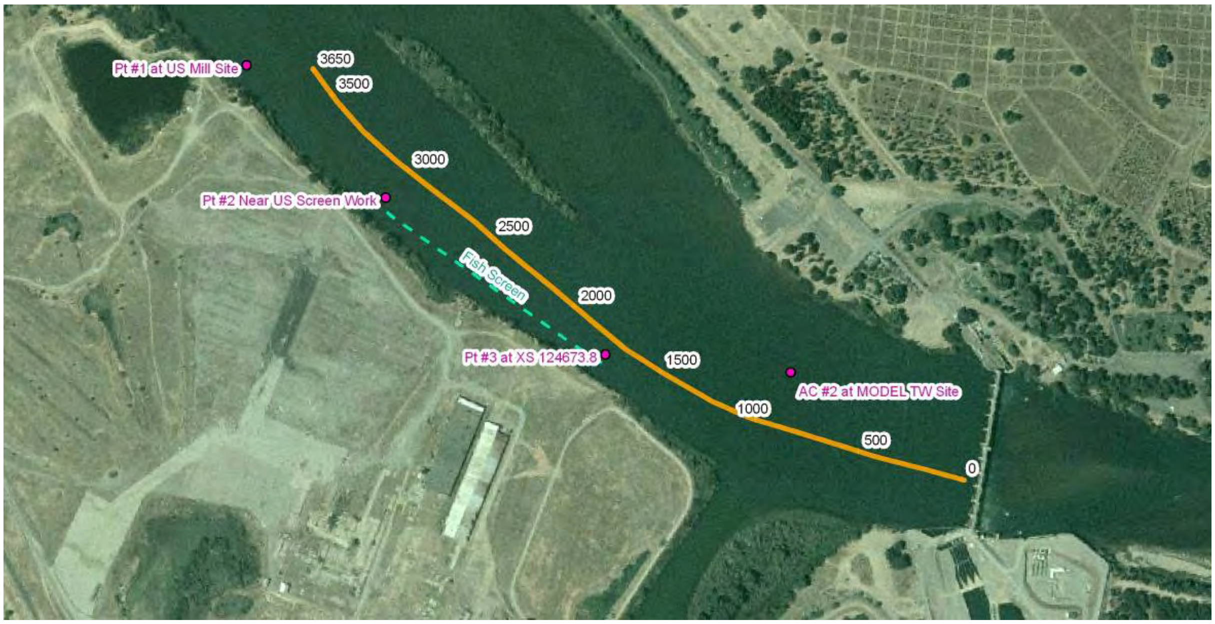

Figure 4. Alignment of water surface profiles and physical model point gage locations.

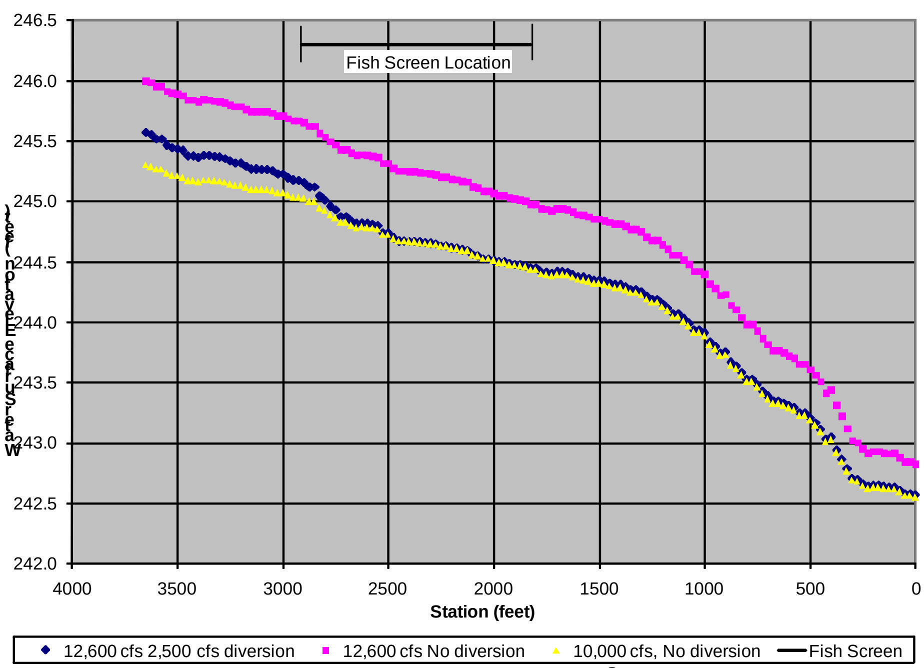

Figure 5. Water surface profiles at 10,000 and 12,600 ft^3/sec with and without diversion.

A comparison was completed between the physical model results and the 2-D model results. There were four point gages where water surface elevations were measured during the physical model tests (Figure 4). The gage data and 2-D model water surface elevation results were compared for similar scenarios at 8,000 and 20,000 ft^3/sec prototype (Table 1). Other than point gage 2, the prototype differences are considered similar and within the error tolerances of the physical and numerical models. Gage 2 may be different because the upstream transition wall has a different geometry in the two models (rounded in the physical model, and blunt in the numerical model). The physical model geometry is closer to the design and these values are assumed to be more accurate.

Table 1. Water surface elevation comparison of physical model and 2-D numerical model results.

	8,000 ft^3/sec			20,000 ft^3/sec		
Point Gage (see Figure 4)	Physical Model	2-D Model	Difference (feet)	Physical Model	2-D Model	Difference (feet)
#1 at US Mill Site	244.299	244.67	0.371	247.701	247.85	0.149
#2 Near US Screen Work Pt	243.602	244.45	0.848	246.92	247.42	0.500
#3 at XS 124673.8	243.884	243.80	-0.084	246.572	246.37	-0.202
Acoustic #2 at Model TW Site	243.094	243.02	-0.074	245.698	245.57	-0.128

The 2-D hydraulic and sediment transport model provided bed elevation change predictions along the proposed fish screen during and after flood events. The area along the majority of the fish screen shows minimal scour or deposition (generally less than 0.25 feet) for the 2-year hydrograph. However, there are localized areas where greater amounts of scour and deposition occurred. The very upstream point of the fish screen has erosion of approximately 0.4 feet due to scour occurring where the fish screen first causes an obstruction. The area at the downstream end of the fish screen shows 4 feet of scour. This is likely due to the hydraulics in this location causing an eddy and eroding the area. An area of deposition occurs downstream of the transition wall where the eroded sediment is locally deposited. Overall, the model predicts minimal bed elevation changes in the area around the fish screen with the 2-year flood event.

The pattern of the bed elevation changes for the 10-year hydrograph is similar to the 2-year hydrograph results. The majority of the fish screen (middle portion) has minimal deposition or erosion (less than 0.25 feet). Immediately upstream of the fish screen is an area of erosion (approximately 1.5 feet). The upstream 250 feet along the fish screen shows up to 1.4 feet of deposition occurring. The deposition is likely due to the flow being directed away from this area by the fish screen’s upstream transition wall. Similar to the 2-year hydrograph bed changes, the area at the downstream end of the fish screen shows increased erosion (up to19 feet). Deposition again occurs downstream of the transition wall. There is approximately 175 feet along the downstream end of the fish screen where the scour depth exceeds 5 feet. It is noted that these results do not include the effects the Tehama formation may have on the scour depth.

The peak of record hydrograph model output at the end of the flood is shown in Figure 6. The red and orange (positive values) show deposition and the blue (negative values) is erosion. The upstream three-quarters of the fish screen have sediment deposition ranging from 0.5 to 3.5 feet. The deposition builds downstream along the fish screen with time. Immediately upstream of the fish screen is a pocket of erosion (approximately 3.6 feet). Similar to the 2-year and 10-year event bed changes, the area at the downstream end of the fish screen has 20 feet of erosion indicating that this area has reached an equilibrium state and will not scour indefinitely. There is about 250 feet along the downstream end of the fish screen where the scour depth exceeds 5 feet.

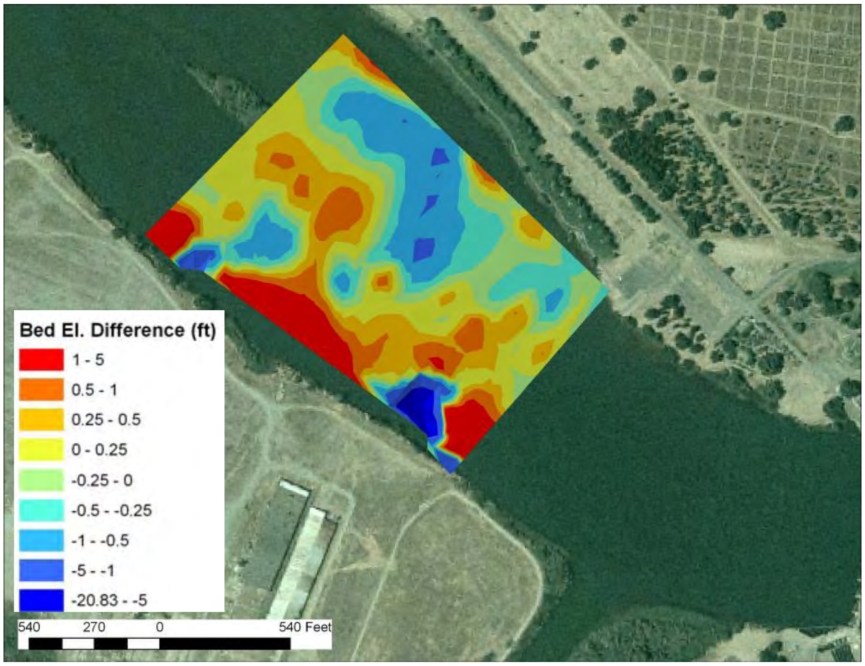

Figure 6. Bed elevation changes near the proposed fish screen after a peak of record flood.

Several physical model tests were conducted to evaluate and measure sweeping velocities (parallel to the screen and positive in the downstream direction) and approach (perpendicular to the screen and negative towards the screen) velocities at several flow and pumping rates. Initial measurements showed that for a wide range of river flows and pumping rates, most of the flow passed through the upstream screens (bays 1-45) and water was flowing out of the pumping plant forebay on the downstream screens (bays 52-60). A nonuniform sweeping velocity distribution was observed downstream of bay 45 and sweep velocities rapidly dropped to below 2 ft/sec at bay 60. This phenomenon was worse for a no pumping condition. Baffles were placed and adjusted in each fish screen bay to improve velocity uniformity along the screen. The results of these tests showed that when bays 1-30 are baffled to 5% open and bays 31-60 are baffled to 7.5% open, there was near uniform approach velocity distribution along the entire fish screen. Average sweeping velocities of 4 and 6 ft/sec were measured for river flows of 8,000 and 12,600 ft^3/sec, respectively. Figure 7 is a plot of approach and sweeping velocities collected for the design river flow of 12,600 ft^3/sec and maximum pumping (2,500 ft^3/sec) after baffling.

The final physical model test evaluated the sediment transport characteristics along the Red Bluff Pumping Plant fish screen structure for a river flow of 80,000 ft^3/sec and no diversion. No sediment was deposited within 25 feet of the fish screen. Observation during the sediment test revealed that sediment moving near the screen was transported away from the screen by secondary currents. Sediment transport capacity beyond Bay 34 was sufficient to move all bedload past the end of the fish screen. After the test, fine sediment accumulation was revealed between the screen and baffles, in each fish screen bay, and to a lesser degree in the forebay.

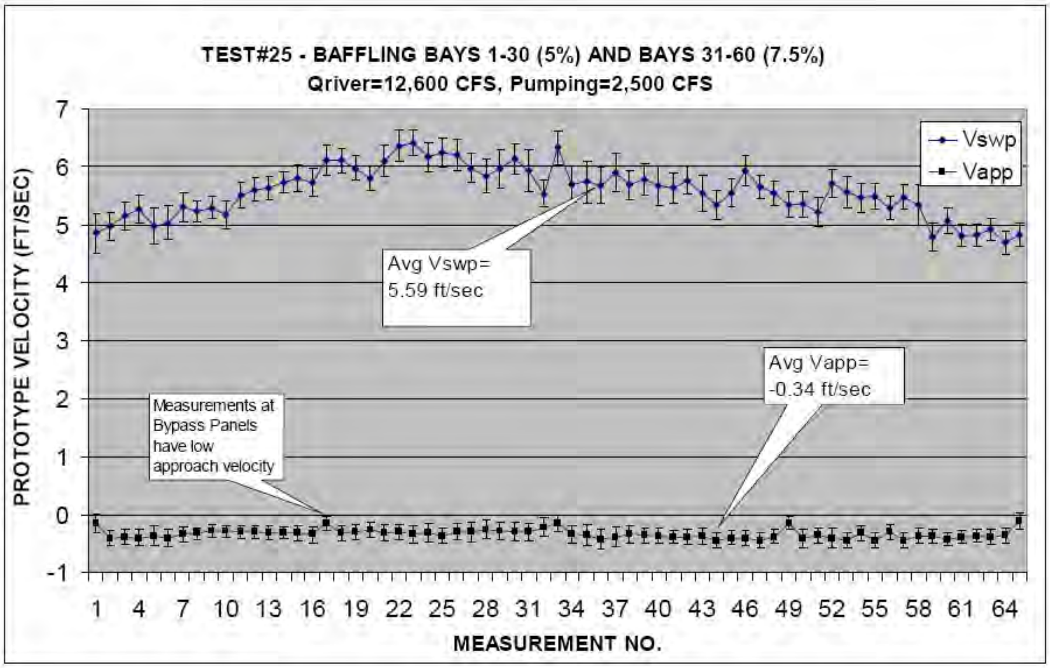

Figure 7. Approach (Vapp) and sweeping (Vswp) velocity components for the fish screen with screen baffles. Error bars represent the standard deviation of the mean velocity components.

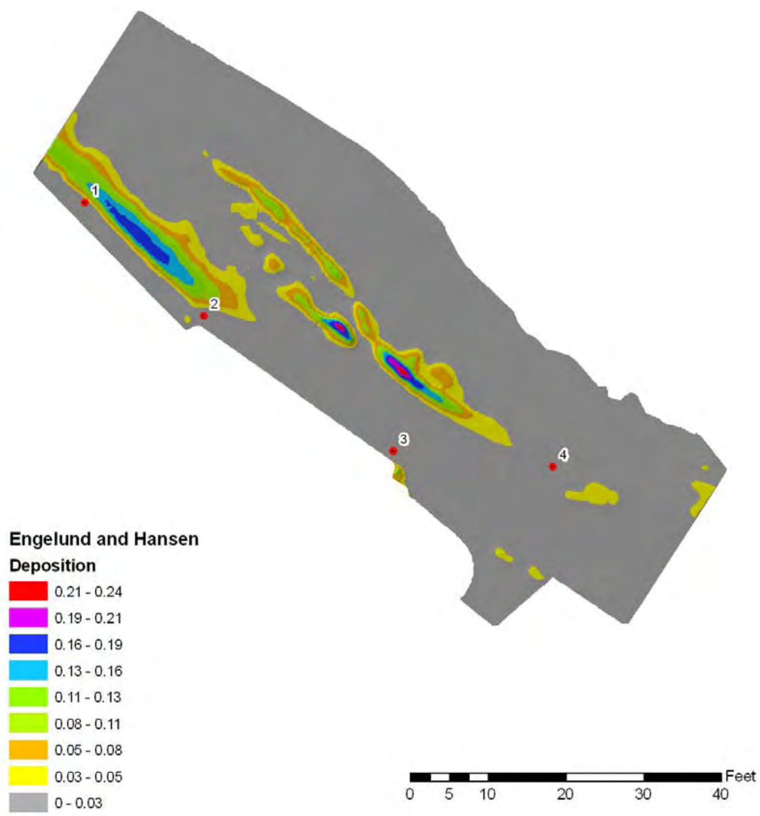

Figure 8. Bed elevation differences from SRH-2D. (Deposition values are in prototype feet).

The resultant sediment depositional patterns from the 2-D numerical model of the physical model were qualitatively compared to the depositional patterns from the physical model. The SRH-2D sediment depositional patterns using the Engelund & Hansen methodology is shown in Figure 8. The upstream ‘pulse’ of sediment seen in the numerical model results (between control points 1 and 2) was also seen in the physical model along with the lack of sediment deposition along the fish screen. The sediment deposition predicted by the 2-D modeling that is located to the left and further downstream of the upstream pulse was not apparent in the physical model and is currently unexplained.

DISCUSSION

Certain variables could be measured in both the numerical and physical models. Water surface elevations compared well and qualitatively the velocities produced in the models were similar. Other variables could only be accounted for in one model due to different model limitations. The sweeping and approach velocities were measured along the fish screen in the physical model. The 2-D numerical model does not have the ability to simulate the baffling characteristics of the fish screen. Therefore, the physical model was used to baffle different bays and evaluate the resulting near-screen velocities. Baffling fish screen bays enabled the approach velocities to have a near uniform distribution along the entire fish screen.

Sediment transport characteristics were qualitatively evaluated in the physical model. No scour potential could be estimated because the model had a fixed bed. There was no sediment deposited within 25 feet of the fish screen face which appeared to be due to observed secondary currents. After testing, fine sediment had accumulated between the screen and baffles of the fish screen. The numerical model of the physical model qualitatively confirmed these results. There was some deposition of sediment upstream of the fish screen and a lack of sediment deposition along the fish screen.

The numerical prototype scale model simulated unsteady flow hydrographs. Erosion and deposition could be estimated because the numerical model had a mobile bed. The entire depth of bed material was assumed to be alluvium although geotechnical borings in the area indicate the Tehama formation is located about 8 feet below the channel bed. The 2-year hydrograph produced almost no deposition or erosion along the length of the fish screen. For the floods equal to or larger than the 10-year and peak of record, scour of 19-20 feet is predicted at the downstream end of the screen and over 5 feet of scour for up to 250 feet of the fish screen length is predicted. Because there is the Tehama formation approximately 8 feet below the channel bed and this is perhaps more resistant to erosion than alluvium, the actual amount of scour could be less. However, the magnitude of the reduction from the 2-D model results is uncertain because the erosion characteristics of the Tehama formation are unknown. The 10-year and peak of record floods show deposition occurring along the fish screen in the numerical model. The secondary flow that was seen in the physical model could not be simulated in the 2-D numerical model and these secondary currents are expected to move sediment away from the screen and reduce or likely eliminate the deposition. However, it is possible that for events near the peak of record some deposition may occur at the front of the fish screen.

CONCLUSION

Multiple models were used to address design issues raised regarding the proposed Red Bluff pumping plant and fish screen. A physical model and two 2-D numerical models of the river channel were used to determine the anticipated water surface elevations in the river with and without diversion as well as the sweeping velocities along the fish screen structure. An additional 2-D numerical sediment and hydraulic model was developed for the 1:42 physical model for verification purposes.

The 2-D hydraulic numerical model simulated a range of flows (normal and flood conditions) with and without diversion and provided water surface elevation profiles along the fish screen. Water surface elevations from the numerical model compared well with the physical model measurements. The physical model provided detailed near-screen velocities along the structure. In addition, the physical model was used to determine effective baffle settings to provide a uniform velocity distribution along the entire fish screen length. Predictions of sediment deposition and scour along the fish screen were developed from the numerical models. The 2-D hydraulic and sediment model was used to determine the location and magnitude of sediment deposition and erosion near the fish screen structure. The 2-year, 10-year, and peak of record hydrographs were simulated in the numerical model. The fixed-bed physical model was able to qualitatively depict deposition zones in the channel and sediment moving through the fish screen and baffles. Based on the secondary flow seen in the physical model, the results of the hydraulic and sediment numerical model were adjusted so that minimal deposition is expected along the fish screen. Erosion is expected along the screen at least to the Tehama formation depth. The models provided overlapping and complementary results to create a more detailed and accurate view of the hydraulic and sediment impacts of the proposed fish screen and pumping plant.

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