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# PHYSICAL MODELING OF THE FOLSOM DAM TAILWATER CONFLUENCE AREA

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## ABSTRACT

Folsom Dam, located upstream of Sacramento on the American River in central California, was designed and constructed by the USACE. The Bureau of Reclamation (Reclamation) has operated Folsom Dam since construction was completed in 1956. Various hydrologic analyses which include the period of record since the project's completion have led to a substantial increase in the identified Probable Maximum Flood (PMF) for the facility, as well as an increase in the identified flood risk for the Sacramento area. To address the dam safety and flood protection concerns raised by the most recent hydrologic information and analyses, Reclamation and the USACE agreed to work together on a Folsom Dam Joint Federal Project (JFP). The current JFP plan includes increasing both the low-level and total release capacities of Folsom Dam through the addition of an auxiliary spillway.

Design of the auxiliary spillway was facilitated through the use of several physical model studies. A 1:48 scale Froude-based model of the proposed auxiliary spillway and the main dam spillway confluence was constructed in Reclamation's laboratory in 2007. This model includes the main dam spillway (all 8 gates) and the lower chute, stepped chute, stilling basin, and exit channel of the proposed auxiliary spillway, their confluence with the American River, and several hundred feet of river downstream from the new bridge across the American River. The primary purpose of the model was to evaluate flow conditions in the confluence area after completion of the JFP. During the design process, the scope of the model study was expanded several times to include evaluations of main dam spillway capacity, energy dissipation on the auxiliary spillway steps, and auxiliary stilling basin performance with various baffle block arrangements designed to minimize cavitation potential. Evaluation of various design concepts in the model proved to be invaluable and led to cost savings in the final design.

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# INTRODUCTION

Folsom Dam is located on the American River about 20 miles upstream from Sacramento, California (figure 1). The dam was designed and built by the COE and transferred to the Bureau of Reclamation (Reclamation) for operation and maintenance in 1956. The existing dam and spillway are comprised of a 340-ft high and 1,400-ft long concrete gravity section flanked on each side by earthfill wing dams that extend from the gravity section to the abutments. In addition to the main section and wing dams, there is one auxiliary dam and eight smaller earthfill dikes that impound a reservoir of 1,010,000 acre-feet. The dam is operated for municipal and agricultural water supply purposes and to provide flood control protection for the city of Sacramento.

Figure 1. Location map of Folsom Dam and Lake upstream from Sacramento, California.

The gravity section of the dam includes an ogee crest at elevation 418 ft for both the service and emergency spillways (figure 2). Releases are controlled using five 50-ft-tall by 42-ft-wide radial gates for the service spillway and three 53-ft-tall by 42-ft-wide radial gates for the adjacent emergency spillway. The service spillway discharges into a 242-ft-wide stilling basin at invert elevation 115 ft while the emergency spillway discharges from a flip bucket into a plunge-pool energy dissipator. A powerplant is located along the right side of the gravity section to which flow is delivered via three 15-ft diameter penstocks. The dam is also equipped with eight outlet conduits through the gravity section, four outlets at elevation 280 ft (upper level) and four outlets at 210 ft (lower level), each having 5-ft by 9-ft slide gates. The downstream ends of the conduits daylight on the service spillway face, but during large floods that produce spillway operation, releases through the outlets are limited. The primary contribution to overall release capacity during flood routing is from the service and emergency spillways.

Figure 2. Concrete gravity section of Folsom Dam.

Dam safety responsibility for Folsom Dam rests with the Bureau of Reclamation. In 2006, Reclamation made a new assessment of the probable maximum flood (PMF) at the dam site that accounted for changes in upstream land use in the preceding 60 years and used flood records including the period since the completion of the dam. Subsequent routing studies show that the existing discharge facilities at Folsom Dam are not capable of safely passing the new PMF. The design and construction of a new spillway or outlet system is thus needed to address this dam safety deficiency. One such alternative for a fuse plug controlled spillway was studied in a physical hydraulic model by Reclamation's Hydraulic Investigations and Laboratory Services Group in Denver, Colorado in 2007.

Separately, beginning in about 1999, the COE and the Sacramento Area Flood Control Agency (SAFCA) studied modifications to Folsom Dam that could increase flood control protection along the American River. The current release capacity of the eight outlet gates through the dam is significantly less than the levee channel capacity of the American River downstream from Folsom Dam. Additional release capacity at reservoir levels below the spillway crest would allow releases during the rising limb of a flood event to approach the river channel capacity, thereby allowing the early release of a larger percentage of the volume of an incoming flood. This would increase the size of the flood that could be successfully accommodated with the existing flood control storage in the reservoir. The objective has been to add facilities capable of routing a 200-year flood event through the reservoir while keeping the reservoir elevation below the crest of the service and emergency spillways and not releasing flows that would overtop levees along the downstream river channel. One proposal to achieve this objective was to increase the size, number, and capacity of the upper and lower level outlets through the dam (Frizell, 2004).

The Joint Federal Project (JPF) combines these independent efforts into one project that meets both Reclamation’s probable maximum flood criteria and the COE’s flood damage reduction goals. Under the JFP, the maximum pool elevation during passage of the PMF was set at elevation 477.5 ft. To maintain at least 3 ft of freeboard during the PMF, discharge routing studies indicated that the required Folsom Dam discharge was 818,000 $ft^3/s$.

To obtain the required discharge capacity and increase flood protection for Sacramento, the JFP includes the construction of a new auxiliary spillway near the left abutment of the main dam embankment (figure 3). The auxiliary spillway is comprised of a control structure that houses six 23-ft-wide by 34-ft-high submerged tainter gates (top-seal radial gates) at invert elevation 368.0 ft, an approach channel from the reservoir to the control structure, a 169-ft-wide rectangular, concrete lined chute, a stilling basin, and an exit channel to return flood discharges to the American River. The downstream section of the spillway chute from Station 32+00 to Station 38+82 was designed as a stepped chute in order to dissipate some energy before flow entered the stilling basin.

Figure 3. Artist’s rendering of the new auxiliary spillway structure to the left of the main dam spillway structure. The new Folsom Lake Crossing Bridge across the American River is shown just downstream from the confluence area.

Several physical and numerical hydraulic model studies were conducted to support the JFP design effort. These studies included a 1:30-scale model of the auxiliary control structure at Utah State University’s Utah Water Research Laboratory (UWRL) and a 1:26-scale model of the auxiliary spillway chute and stilling basin at the University of Minnesota’s St. Anthony Falls Laboratory (SAFL). In addition, Reclamation’s Hydraulic

Investigations and Laboratory Services Group conducted both numerical and physical modeling of JFP project features at the Technical Service Center in Denver, Colorado. This paper summarizes one of those studies, a 1:48-scale physical model of the main dam spillway, the new auxiliary spillway and stilling basin, the confluence area of the two exit channels, and a portion of the downstream river. This model, often referred to as the Confluence model, was constructed and tested by Reclamation from 2007 to 2009.

## CONFLUENCE MODEL

### Model Objectives

The primary purpose of the Folsom confluence model study was to evaluate the three-dimensional characteristics of the flow in the vicinity of the confluence of the main dam exit channel and the auxiliary spillway channel, particularly with regard to energy dissipation and the interaction between flow from the primary and auxiliary spillways. The study was intended to address both design and operational issues.

The initial goals of the study included documenting water-surface profiles and flow velocities in the confluence area for various combinations of individual and combined releases from the main dam and auxiliary spillway. Issues of particular concern included velocities in the vicinity of the right bank (opposite the new auxiliary spillway), and hydraulic forces on the right auxiliary stilling basin wall. Additional issues were raised during various phases of the model design, construction, and testing. These issues included defining the main dam spillway capacity, defining cofferdam heights for dewatering the auxiliary stilling basin construction area, and verifying the auxiliary stilling basin energy dissipation performance.

### Model Description

A 1:48-scale was chosen for the Folsom confluence model in order to reproduce as much of the project extents as possible within the available space and discharge limitations of the laboratory. The model included a 25-ft-wide by 22-ft-long by 7-ft-high rectangular headbox for the main dam and a 12-ft-wide by 11-ft-long by 7-ft-high rectangular headbox for the auxiliary spillway structure, both elevated 3.7 ft above the laboratory floor. A large nonrectangular tailbox was constructed to follow the course of the American River channel with a return channel to carry flows back to the laboratory sump (figures 4 and 5).

The model included representations of the main spillway and eight crest gates along with 1000 ft of reservoir upstream of the dam, the downstream end of the auxiliary spillway including 500 ft of smooth chute and the stepped spillway drop into the auxiliary stilling basin, and the confluence area of the downstream channel extending approximately 500 ft beyond the new Folsom bridge. Tailwater elevations at the downstream end of the model were controlled with a slide gate to reproduce water levels determined from a COE HEC-RAS backwater model for various project discharges.

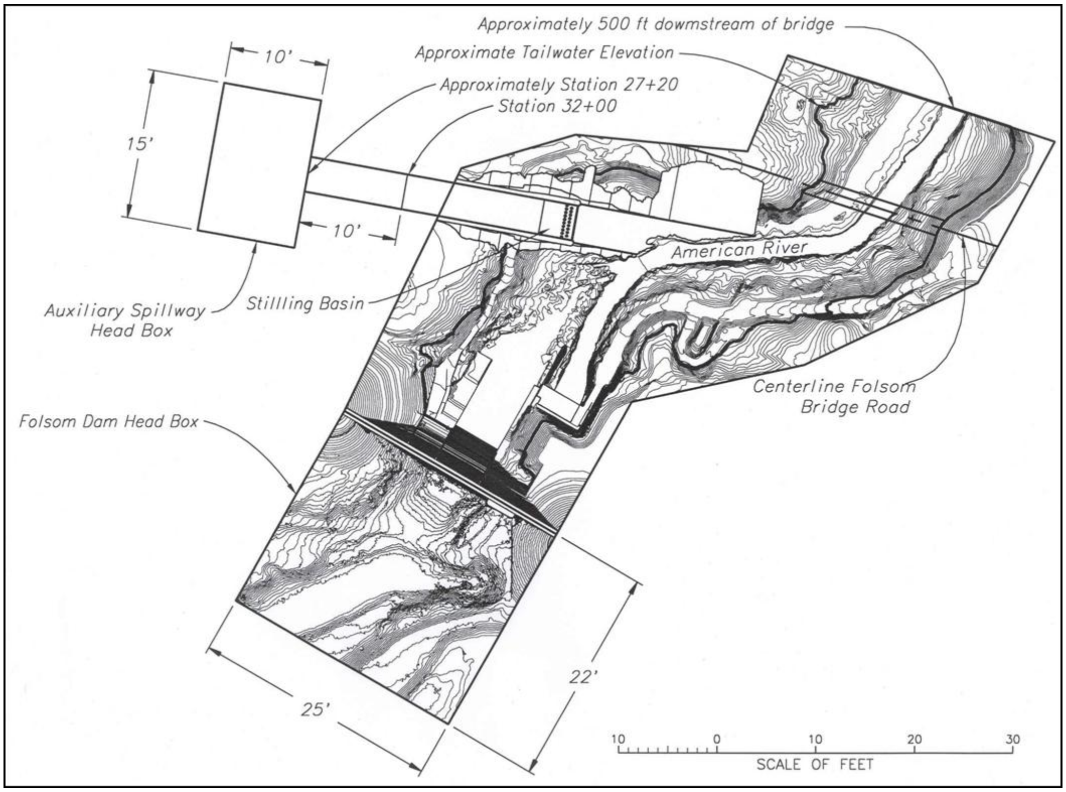

Figure 4. General layout of the 1:48-scale Folsom Dam confluence model.

Figure 5. 1:48-scale physical hydraulic model of the main Folsom Dam, auxiliary spillway, and confluence area where flows combine in the American River.

# MODEL TESTS

## Main Dam Spillway Capacity

During construction of the confluence model, concerns were raised about the total discharge capacity of the JFP, and the uncertainty of discharge rating information for the main spillway at PMF conditions. To address these concerns, the model was temporarily modified to allow for detailed discharge rating measurements at gate-controlled PMF conditions including reservoir pool elevations of 477.5 ft and gate openings of 35 to 40 ft. The data collected from these measurements was combined with additional information from a computational fluid dynamics (CFD) study and a 1:36-scale sectional model to demonstrate that at a reservoir elevation of 477.5 ft and a gate opening of 40 ft, the 8-gate spillway capacity of the main dam was 518,000 $ft^3$/sec. This exceeded the original routing estimates of main dam spillway capacity by 3 percent, and ensured that the JFP combined release capacity (main dam plus auxiliary spillway) would exceed the project requirement of 818,000 $ft^3$/sec.

## Cofferdam Design

Construction of the auxiliary stilling basin is expected to require both the addition of a haul road down to the basin location, as well as a cofferdam to protect the work zone in the event of spillway releases from the main dam. The alignment of the haul road along the left side of the main dam stilling basin exit channel created a path for spillway releases to carry rocks and other material directly into the auxiliary stilling basin exit channel. To minimize the likelihood of this occurring, it was decided to make part of the cofferdam wall along the haul road a permanent structure to divert smaller spillway releases away from the auxiliary stilling basin.

The confluence model was modified to include the proposed cofferdam and haul road in the topography (figure 6). Water-levels along the cofferdam were then observed for main dam discharges ranging from 30,000 to 100,000 $ft^3$/sec. Ultimately, 50,000 $ft^3$/sec was selected as the design discharge for cofferdam protection, and the wall height was designed based on the associated water-levels observed in the model.

Figure 6. Installation of plywood cofferdam sections in the model. Model topography was modified to incorporate the construction access road.

## Auxiliary Spillway Performance

The design and performance of the auxiliary spillway and stilling basin were initially tested in the 1:26-scale SAFL model. Additional testing related to the performance of the auxiliary stilling basin and stepped spillway was performed using the 1:48-scale confluence model.

Tailwater Sensitivity: Tailwater sensitivity tests were conducted at auxiliary spillway flows of 115,000 $ft^3/s$ and 160,000 $ft^3/s$ to determine the degree to which acceptable stilling basin performance was sensitive to the tailwater setting. These tests were conducted with the seven original, standard-shaped baffle blocks (16 ft high by 12 ft wide by 19 ft deep with a 1:1 sloping back face and 3 ft flat top) in one row at Station 39+71 with the 15-ft-high end sill installed from Station 41+00 to 41+32.

For each flow rate, the initial tailwater elevation in the model was set to the value approximated by the HEC RAS prediction at cross section 28.6555. Flow conditions in the auxiliary stilling basin and exit channel were observed and photographed. The tailwater elevation was then lowered in the model. Flow conditions were allowed to stabilize and the process was repeated until the auxiliary stilling basin performance was no longer acceptable.

For a discharge of 115,000 $ft^3/s$, the auxiliary stilling basin performance was reasonable for the entire range of tested tailwater conditions (up to 7 ft lower than the HEC-RAS predicted elevation). For the 160,000 $ft^3/s$ condition, the basin performance was much less robust. At a tailwater elevation of 183.9 ft (0.1 ft below the HEC-RAS prediction) the basin performance was acceptable although periodic splashing over the sidewalls was observed. At a tailwater elevation of 183.0 ft (1.0 ft below the HEC-RAS prediction) the basin performance began to deteriorate. Surging began to develop in which the toe of the jump was pushed toward the baffle blocks creating a significant uplift of the water surface which then collapsed back on itself and pushed the jump back upstream. This process repeated itself in a cyclic fashion, with significant overtopping of the basin walls during the upswell periods.

<u>Stepped versus Smooth Chute Performance</u>: The auxiliary spillway was designed as a stepped spillway to dissipate as much energy as possible before the flow reached the stilling basin. Late in the design process questions were raised concerning the benefit of the steps with regard to overall stilling basin performance. To help address these questions, the stepped spillway portion of the auxiliary spillway was covered by sheet metal to provide a qualitative comparison of stilling basin performance between a stepped spillway chute and a smooth spillway chute. Seven different flow conditions were evaluated and compared between the two spillway types. The observations from these comparisons clearly indicated the performance benefit of the stepped spillway. The smooth chute resulted in flow conditions in the basin that were unacceptable, with the hydraulic jump often sweeping past the basin baffle blocks and resulting in a jet of water directed upwards as supercritical flow impacted directly on the blocks. To make the basin performance acceptable under these conditions, the tailwater needed to be raised by 10 ft. To achieve this effect in the prototype, the basin floor would have to be lowered 10 ft, which would result in prohibitive excavation costs.

<u>Baffle Block Performance</u>: CFD studies indicated that flow velocities entering the auxiliary stilling basin could range from 100 to 130 ft/sec (Kubitschek, 2008). Under these conditions it was expected that cavitation would occur around a conventional basin baffle block. A separate physical model study of cavitation potential was conducted in Reclamation’s low ambient pressure chamber. This study resulted in an alternative baffle block shape that would minimize the potential for cavitation damage on or around the blocks (Frizell, 2009a), along with several alternative combinations of the blocks and an associated floor ramp. The alternative block and ramp combinations identified in this study were evaluated in the confluence model to determine how they affected the overall performance of the basin. From these tests a combination of the alternative block shape with ramps located between the blocks (figure 7) was identified as having the best combination of basin performance and cavitation minimization.

Figure 7. Looking upstream at the cavitation-reducing baffle blocks with a 4-ft-high by 12-ft-long ramp on a 3:1 slope between the blocks.

## Hydraulic Forces on Auxiliary Basin Wall

The right wall of the auxiliary stilling basin projects into the path of water discharging from the main dam spillway. With water on both sides of the wall, there is a potential for differential loading on the wall if the water surfaces on one side differ from those on the other. To evaluate the differential loading, water-surface elevations were measured on each side of the wall using capacitance wave probe sensors located on both sides of the wall at several locations along the length of the wall. Measurements were made under various flow combinations, and these measurements were used to evaluate the maximum differential in water levels across the walls.

The structural designers of the wall requested additional information in the form of dynamic pressure measurements collected simultaneously on both sides of the wall. These measurements were made, and the results were consistent with the wave-probe data. From the data collected with both the pressure transducers and wave probe, a typical design approach of accounting for a full height static differential across the 66-ft-high wall appears conservative as the maximum mean values of pressure differentials were of the order of slightly more than one-half of the wall height (about 41 ft of water). Frequency analysis of the differential time series denoted no periodic forcing at any flow condition tested

## Water-surface Profiles

Water surface elevations were measured throughout the model with piezometer taps on the bed of the model. Water levels on the manometer boards were visually averaged and recorded. Water surface elevations were measured in the main dam exit channel, downstream from the emergency spillway, in the auxiliary stilling basin and exit channel, outside of the right auxiliary stilling basin wall, in the American River channel, and along the left and right banks looking downstream. Data were collected during 20 flow combinations with release flows divided between the auxiliary spillway and the main dam. All tap locations at the centerline of the American River channel were 100 ft apart.

Water-surface profile information combined with visual observations and photographic documentation were used to evaluate and compare different operational scenarios ranging from all discharge from the main dam to all discharge from the auxiliary spillway to discharge split between the two structures. For a given total discharge, flows released concurrently from the two structures appear visually to have better energy dissipation characteristics. This is largely due to the reduced velocity (lower Froude number) entering each structure versus what would be present had all flow been diverted into a single spillway and stilling basin. This same reasoning results in lower wave heights along the banklines for the concurrent operations.

## Velocities

Flow velocities were measured in various locations in the American River channel and the auxiliary spillway exit channel. These data are being used to evaluate bank stability and erosion concerns in the confluence area and downstream in the river channel. Velocity data were collected with a handheld SonTek 2-D FlowTracker acoustic velocimeter for 20 discharge combinations.

Velocities were measured at 15 locations in the physical model at 0.6 times the total depth from the water surface at a sample rate of 1 Hz for 40 seconds (4.6 minutes prototype). Figure 8 shows the measurement stations and velocity orientations. Measurement stations 1-10 were located in the American River channel. Due to the 10 cm (3.94 inch) offset of the sampling volume from the probe position for the FlowTracker instrument, velocity data were collected approximately 5 inches from the right bankline in the model, corresponding to 20 ft prototype. The velocimeter was oriented so that the positive X velocity vector pointed downstream and the positive Y velocity vector pointed toward the left bank (figure 8).

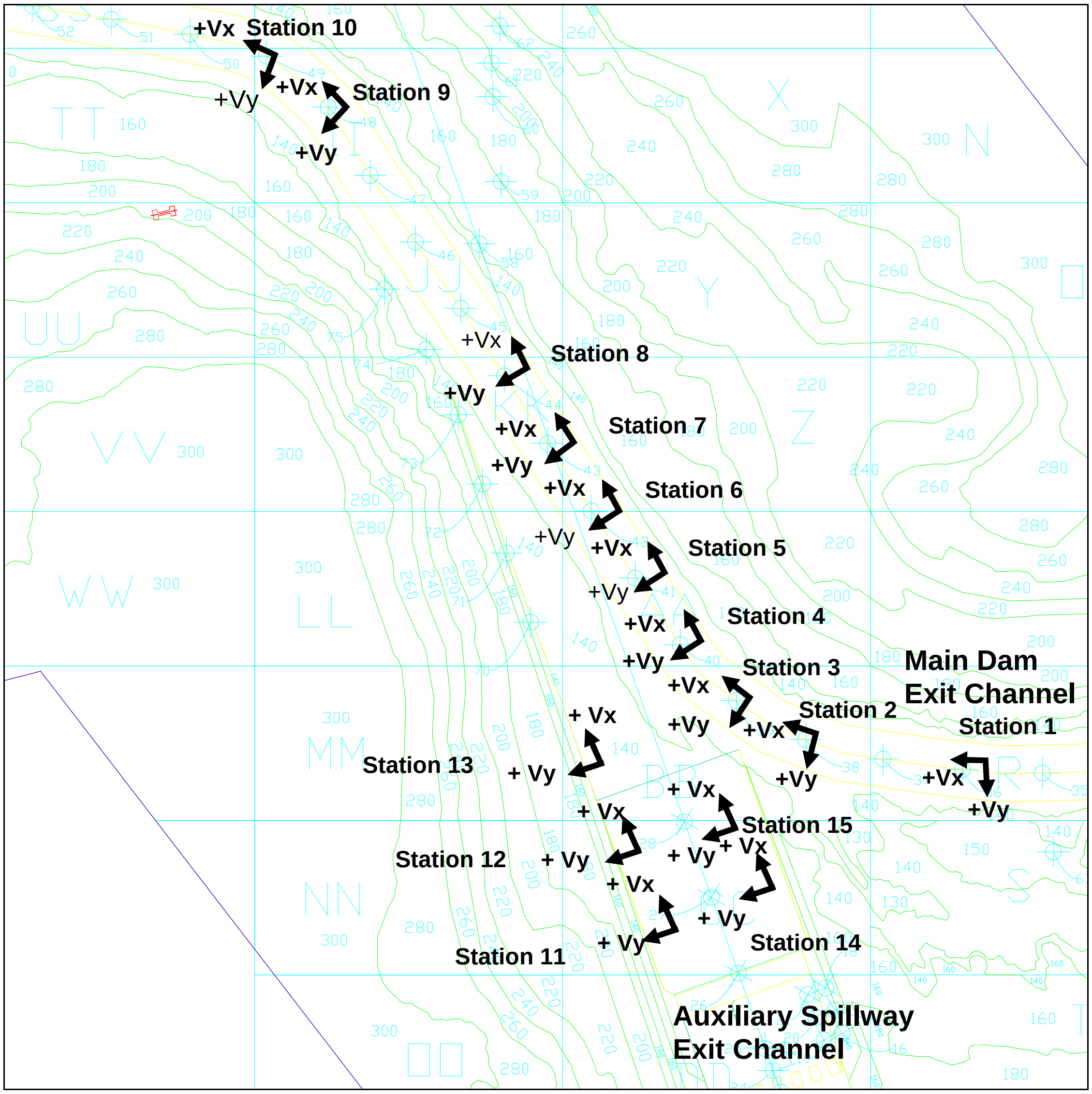

Figure 8. Velocity measurement locations and instrument orientation.

## CONCLUSIONS

The confluence area of the Folsom Dam auxiliary spillway and main dam was modeled using a 1:48-scale physical model. This modeling effort was combined with several other physical and numerical model studies to support the design effort of the Folsom JFP to enhance dam safety and increase flood protection. The use of both physical and numerical modeling in support of the JFP led to improvements in the project design and substantial cost savings. Physical modeling continues to play an important and indispensible role in the design and analysis of hydraulic structures, demonstrating not only the positive performance of a particular design, but also potential improvements to the design for both cost and performance benefits. The Folsom Dam confluence model continues to be used for ongoing evaluations of proposed operational rules, and as a support tool for project planning.

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