PAP-889

Red Bluff Diversion Dam
Fishway Attraction Study

Spillway Operation Test

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Conducted for
Red Bluff Field Office

by

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Background

Red Bluff Diversion Dam was constructed in the mid 1960's. The dam spans the Sacramento River with eleven 60-ft wide spillway gates. Plan and sections of Red Bluff Diversion Dam and stilling basin are presented in figure 1. All spillway gates can be operated in automatic mode using an upstream lake elevation target. However, typical operation of the spillway gates has gates one through ten manually changed in response to large changes in river flow. Gate 11 operates in auto mode to regulate the upstream water surface for gravity diversion to the Tehama Colusa Canal. Downstream of gates one through ten is a Type II hydraulic jump stilling basin with a concrete apron and solid endsill. Downstream of gate 11 is a Type III hydraulic jump stilling basin. Both stilling basins have experienced significant abrasion damage over the past 40 years. Damage has occurred primarily near the basin chute blocks and endsill. The Designer's Operating Criteria (DOC) for spillway gate operation was revised in 1970 to address the problem of concrete abrasion in the stilling basins. The criteria places two constraints on spillway operation. First, the DOC requires gate 11 (sluice gate) be operated at a minimum of 2,500 cfs prior to opening any of the other 10 spillway gates. This ensures hydraulic jump stability by providing sufficient tailwater for Type II stilling basins. Second, gate openings of adjacent gates 1 through 10 shall not exceed a 1.0 ft differential. These revised operating criteria ensure flow releases through the gates are sufficiently uniform to produce a stable hydraulic jump and reduce erosion and abrasion damage to the downstream apron. Current gate operation criteria were established via a memorandum to central files by Ray Willis, Irrigation and Operation Branch, Division of Water and Land Operations, July 22, 1971.

The issue of fish passage attraction and spillway gate operation has been the subject of discussion since the early 1970's. The three main references prior to this report are; a travel report by Carlson and Kuemmich (1971), a Memorandum to Director of Design and Construction, 1975 and a Memorandum from Johnson to the Red Bluff Program Manager, 1995. In addition, other related work includes a hydraulic model study of a concept for constructing enlarged ladders, (Kubitschek, J., 1997) and a field study of the flow conditions at the entrance to the right bank ladder, (Kubitschek, J., et al. 1997). These studies show the fishway attraction flows are often masked by uniform spillway releases and more flexibility in lateral adjustment of flow releases could potentially improve attraction to the abutment fishways.

Study Objective

In August 2001, a series of field tests were conducted to investigate hydraulic conditions in the stilling basin and downstream river that result from non-uniform spillway gate operation. The tests focused on the effect of center dominated spillway releases with respect to stability of the hydraulic jump, abrasion damage potential, erosion downstream of the endsill and downstream flow patterns near the north and south bank fishway entrances.

Test Plan

Three tests of different spillway gate openings that provided center dominated spillway releases were conducted during the week of August 13, 2001. Test procedures followed a pre-test plan submitted to Red Bluff Diversion Dam Field Office June, 2001. Each spillway test consisted of examining the spillway apron, riprap, and downstream bathymetry, videoing surface flow conditions, and measuring the velocity field downstream of the spillway apron for a distance of approximately 1000 feet. Each test condition was held constant for about 20 hours to allow sufficient time for alluvial material to move in response to the flow conditions. After each test period, bays 10 and 11 were inspected. Spillway releases were then moved from the center bays to bays 10 and 11 to complete the inspection of other bays. During this period, downstream bathymetry was also mapped to identify changes that took place during the previous test. The velocity field in the river downstream of the spillway was measured during each centered dominated spillway release.

Testing

During the test period, river flows were 3,000 to 4,000 ft^3/s below expected levels. Because of this, proposed spillway gate openings cited in the original test plan had to be reduced. River flows past the dam started at 11,550 ft^3/s on 8/13/01 and decreased daily to 10,110 ft^3/s on 8/17/01. River flows are a combination of spillway flow and right and left bank fishway flows. Spillway flows during tests 1, 2, and 3 were approximately 9,200 ft^3/s, 9,000 ft^3/s and 8,500 ft^3/s, respectively.

A dive inspection of the spillway apron and downstream riprap was conducted prior to the first test and following each test. Please refer to attached dive report for detailed information. Divers were asked to identify major movement in sediment deposits on the spillway apron, conditions of downstream riprap and document damaged spillway concrete for future reference.

Spillway hydraulic parameters are based on a previous hydraulic model study conducted by Dodge in 1963. Spillway gate setting, reservoir elevation and tailwater elevation were recorded during the testing. Test conditions during each test are given in tables 1, 2, and 3 and are plotted in figure 2. During testing large flows were released through gates 5, 6, and 7 with little or no flow through the remaining gates. The largest test flows were always passed through gate 6.

During pre-test and river centered operations, river flow velocities and depth were measured in the area starting approximately 40 ft downstream of the spillway endsill and extending about 250 ft downstream of the fish screen bypass outfall. Velocity profiles and bottom depth were measured using a boat-mounted Acoustic Doppler Current Profiler (ADCP). Boat access for making measurements was limited to areas outside the bubble plume downstream of large gate openings and areas where flow depth was greater than two feet. Because of changes in river bathymetry, boat traverses could not be exactly repeated during each test, therefore the measured data was interpolated onto a square grid for comparison of different tests. River bathymetry was measured following each test concurrent with the dive inspection of the spillway. This data was also interpolated onto a square grid.

Pretest Conditions - Due to fish passage concerns in recent years, operation of the dam has changed to 4 months with spillway controlled flow releases referred to as "gates-in" and 8 months with "gates-out" (gates fully open). The gates are typically used to control flow releases from May 15 to September 15. During "gates-in" operation, a temporary fish ladder is installed in bay 6 that prevents the gate operation. The fish ladder was removed one week prior to the spillway tests. Existing guidelines for spillway releases with the center fish ladder installed and without the center ladder in place are given in tables 4 and 5. The existing gate position guidelines restrict the difference between adjacent gate openings to less than 1 ft and recommend the highest flows in the outer bays adjacent to the left and right bank fishway entrances. The Red Bluff Diversion Dam record of operation prior to the tests for the month of August 2001 is given in table 6. The flow field as denoted by depth averaged velocity vectors measured downstream of the spillway on August 13 is given on figure 3. The velocity vectors show flows from the outer gates merge as the river narrows about 700 ft downstream of the dam. Flow patterns closer to the dam were fairly chaotic. The bank weighted flow releases and the influence of downstream sediment deposits caused a large area of poorly defined flow direction downstream of bays 3 through 8 for a distance of about 600 feet. The concave spillway flow release pattern results in bed material deposits in the center of the river and deep near-bank channels downstream of each fishway entrance. In the center of the river, the gravel bar started on the spillway apron and extended well downstream from the dam. Divers estimated gravel deposits of about 20 yd^3 in spillway bays 5, 6, and 7, and 10 yd^3 in bay 8. Please refer to the attached dive report. River bathymetry measured downstream of the spillway is given on figure 4. The bathymetry data reveals scoured areas greater than 10 ft deep downstream of the gates 1 and 2 near the west banks and gates 10 and 11 on the east bank. There was a large area downstream from gates 5, 6, and 7 where flow depth was less than 2 feet. The scoured areas are probably characteristic of the pre-test gate opening pattern, however, a major influx of sediment from Red Bank Creek in the past year and short term sediment flushing operation using bays 10 and 11 also contributed to the pre-test bathymetry.

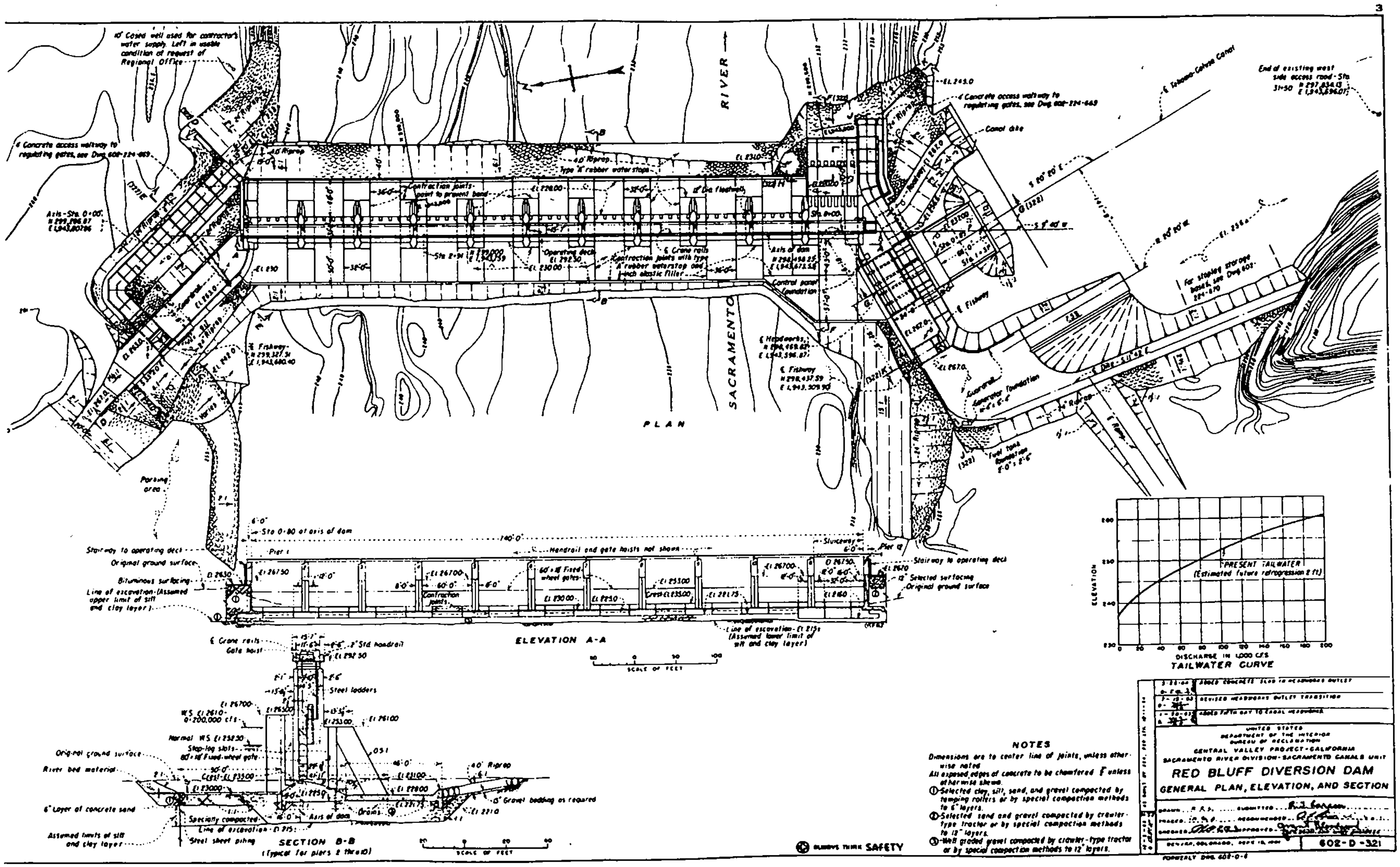


Figure 1- Plan and sections of Red Bluff Diversion Dam.

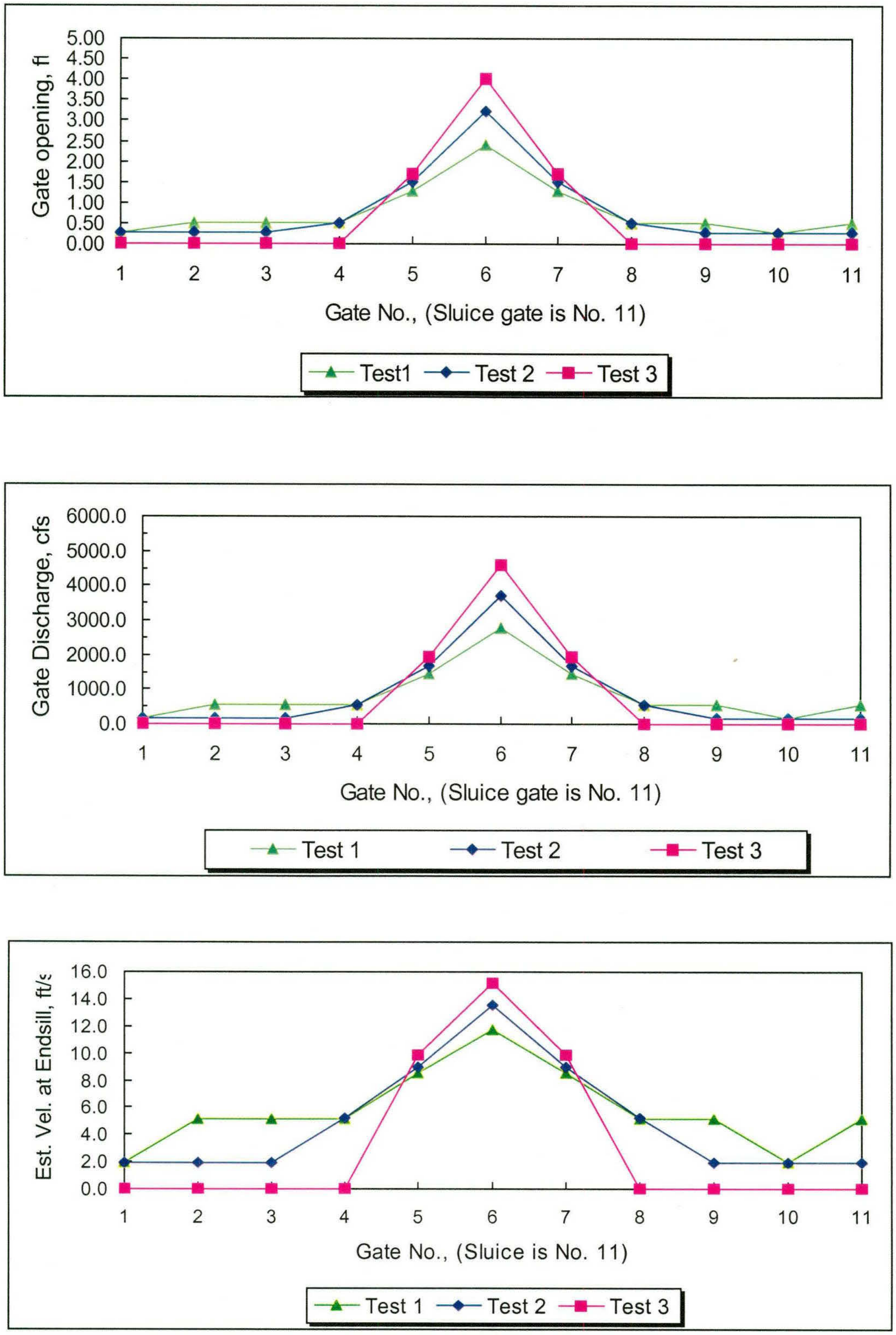


Figure 2 - Spillway operation for tests of river centered releases.

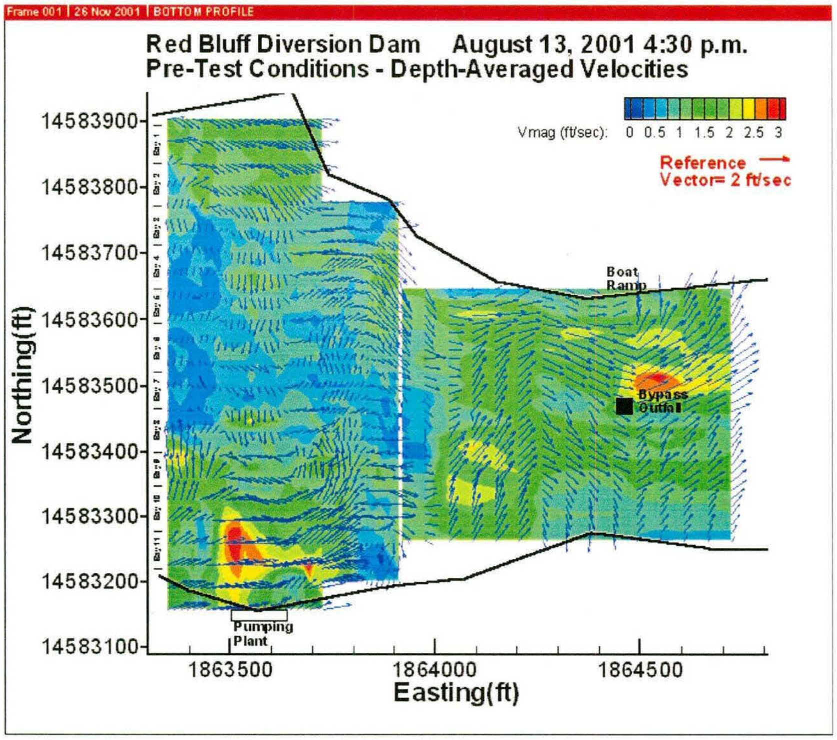


Figure 3 - Pretest depth-averaged velocities downstream of Red Bluff Diversion Dam.

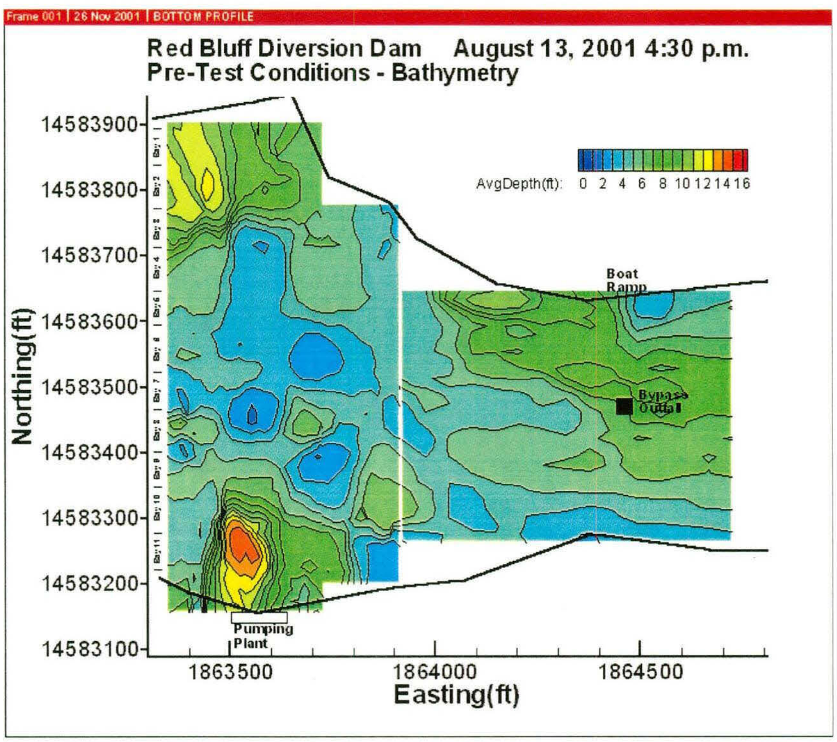


Figure 4 - Pretest river bathymetry downstream of Red Bluff Diversion Dam.

Results

River Center Spillway Release Test 1

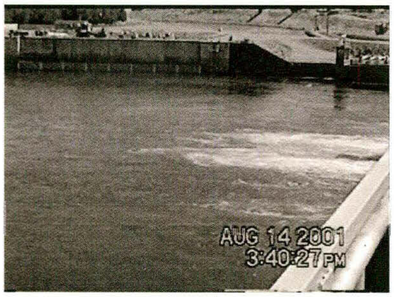
The objective of test 1 was to evaluate spillway hydraulic conditions during a strong centered spillway release combined with smaller sediment flushing flows from all other gates. Gates 2, 3, 4, 8, 9, and 11 were opened 0.5 feet. Gates 1 and 10 were only opened 0.25 feet due to low river flow. Gates 5, 6, and 7 were opened 1.25, 2.4 and 1.25 feet respectively, giving a 1.15 feet difference between adjacent gates. The 0.5 ft gate opening used for outer gates was selected based on an estimated average flow velocity at the endsill of 5 ft/s.

Hydraulic Jump Stability - Releases from gates 5,6, and 7 produced a bubble plume that extended to approximately the spillway endsill (figure 5). The hydraulic jump downstream of gates 5, 6, and 7 appeared very stable. The gate openings tested provided a ratio of tailwater depth to hydraulic jump conjugate depth greater than one for all gates (table 1). Reclamation Engineering Monograph 25 recommends a ratio greater than 1 for good jump stability.

Spillway Apron Abrasion Damage Potential - The large gravel deposit downstream of the spillway center gates significantly effected downstream flow conditions. River bathymetry and the downstream flow field continually changed during the tests as material was scoured from the center of the channel and redeposited to the sides and downstream. The flow from gates 5, 6, and 7 spread to both sides of what was almost an island of alluvial material. Significant amounts of gravel were flushed from the spillway apron during the test. Divers estimated that the quantity of gravel on the spillway apron was about 50 percent of pre-test conditions after test 1 (Dive Report - table 1). All material was removed from bays 6 and 7 and the amount of material in bays 5 and 8 was reduced by about one-half. Some material did redeposit near the endsill in Bays 3 and 4 where no material was found during the pretest inspection. All alluvial material found on the spillway apron was located near the endsill.

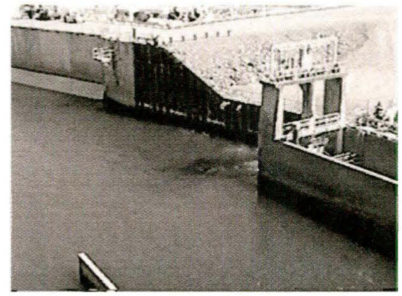
River Bathymetry and Flow Conditions Downstream of the Spillway - Figure 6 gives the post test river bathymetry. Figure 7 shows the change in depth between pre and post test 1 conditions. Scouring in the center of the river was accompanied by deposition near each bank downstream of the fishway entrances. The large river center flows scoured material downstream of gates 5,6, and 7 exposing the spillway apron endsill and downstream riprap. Deposition of 6 ft to 8 ft occurred in front of the pumping plant downstream of bays 10 and 11 and downstream of bays 1 and 2. The rapid movement of material toward the river banks was driven by the lateral spread of spillway releases as the flow impacted the extensive alluvial deposit immediately downstream of the center gates. The dive inspection indicated the riprap was not affected by the test flow. River velocities measured during the test using an ADCP are given in figure 8. The flow field for a distance of nearly 600 ft downstream of the dam is poorly defined due to sediment deposits and the wide channel. Strong flows were measured about 300 ft downstream of the spillway apron along both river banks. The flow likely resulted from the movement of spillway flow around the river centered deposits rather than fishway flows. The ADCP data shows fishway flow rapidly mixed with spillway flows. Fishway flow velocities were not discernable from other spillway driven flow velocities beyond 50 to 75 ft downstream of the fishway entrance.

Figure 5 - Photographs of surface flow conditions during test 1.



View of white water turbulence downstream of gates 5, 6 and 7.

View of surface flow conditions downstream of the left bank fishway.



View of surface flow conditions downstream of the right bank fishway.

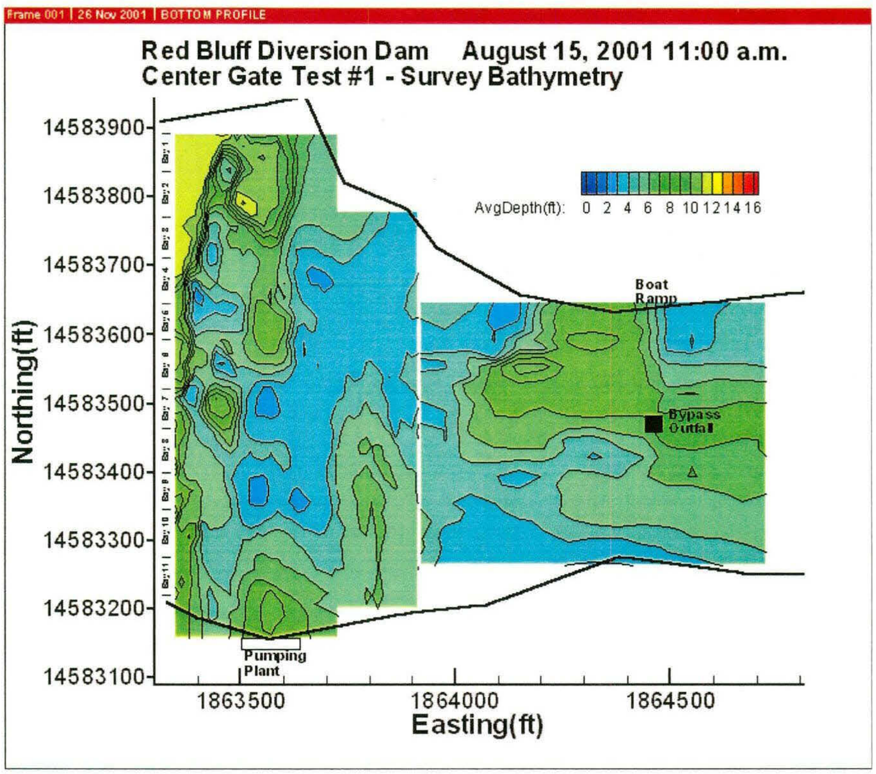


Figure 6 - River bathymetry downstream of Red Bluff Diversion Dam after test 1.

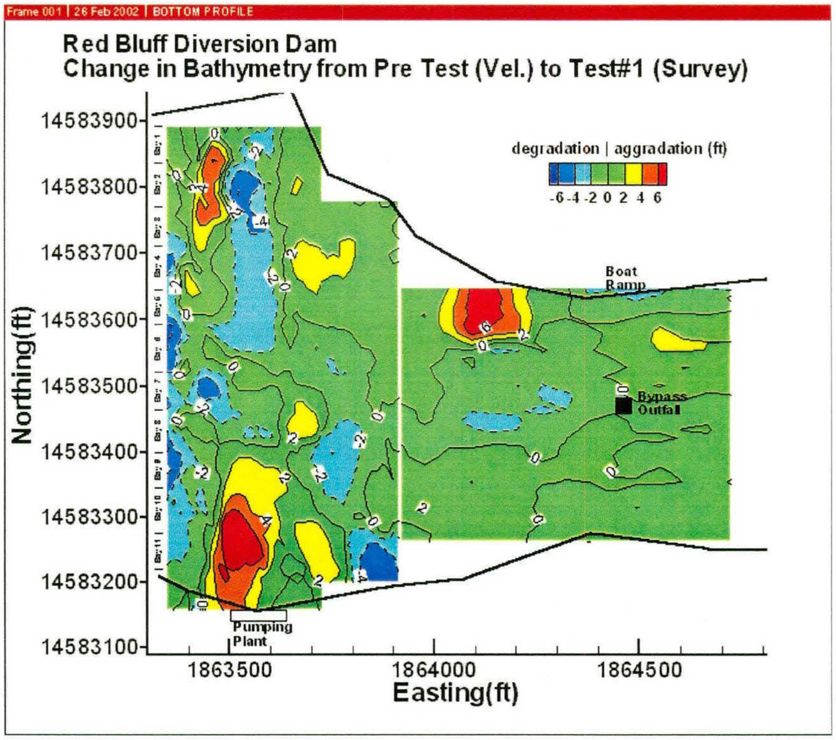


Figure 7 - Change in river bathymetry from pre-test to test 1.

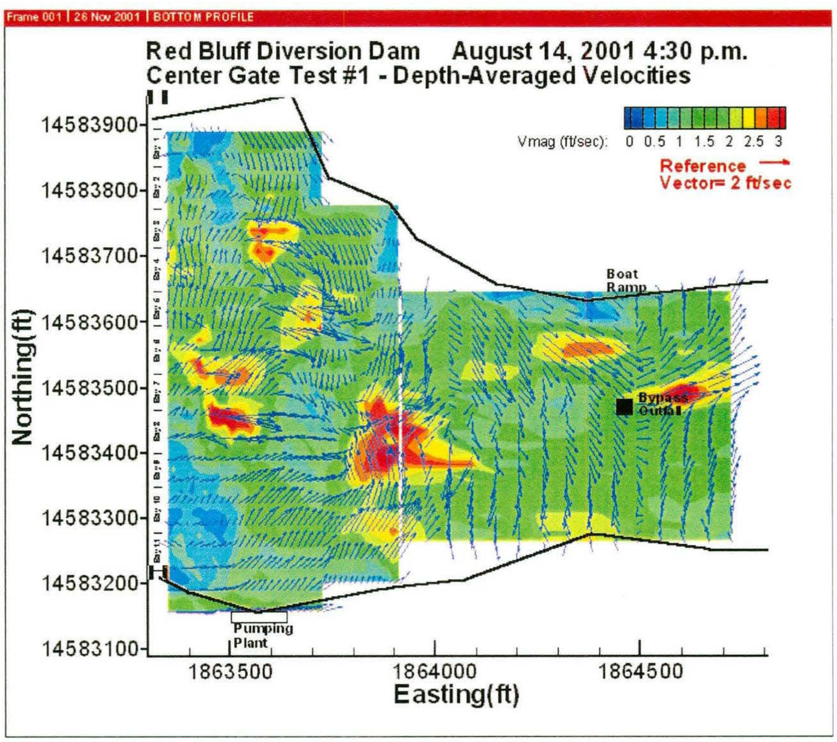


Figure 8 - Test 1 depth-averaged velocities downstream of Red Bluff Diversion Dam.

River Center Spillway Release Test 2

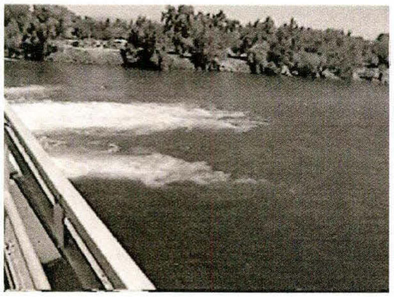
The objective of the second test was to further concentrate flows to the center of the spillway and test a gate opening differential between adjacent center gates significantly higher than 1 foot. Prior to test 2, center releases were increased and outer gate flows decreased. Gates 1, 2, 3, 9, 10, and 11 were opened 0.25 feet. Gates 4 and 8 remained at a 0.5 ft gate opening. Gates 5, 6, and 7 were opened 1.5, 3.2, and 1.5 ft respectively, giving a 1.7 ft differential between adjacent gates, (table 2). The 0.25 ft gate opening used for outer gates produced an estimated average flow velocity at the endsill of 2 ft/s. Gates 4 and 8 were maintained at a 0.5 ft opening to provide a stronger spillway apron flushing flow adjacent to the larger gate openings.

Hydraulic Jump Stability - Releases from gates 5, 6, and 7 produced a bubble plume that extended well beyond the spillway endsill, as shown in figure 9. The hydraulic jump downstream of gates 5, 6, and 7 remained stable with the increased flow of test 2. The gate openings tested provided a ratio of tailwater depth to hydraulic jump conjugate depth greater than one for all gates, (table 2).

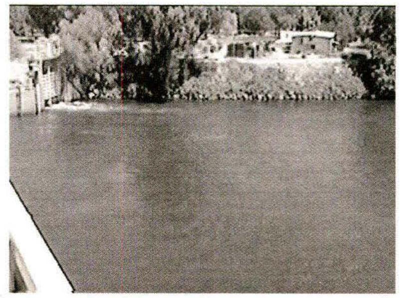
Spillway Apron Abrasion Damage Potential - After a day of operation the flow scoured alluvial material from the spillway apron and cut several new channels through the large downstream gravel deposit. Following the test, divers found about 50 percent of the material remaining in the basin after test 1 had been removed. Material in bays 3, 4, and 5 was reduced by about 90 percent and material in bay 8 increased by about 60 percent. All gravel deposits were again located immediately upstream of the spillway apron endsill. Divers noted that a fine cover of moss attached to the spillway apron showed no evidence of abrasion upstream of the endsill as a result of the concentrated high velocity flows.

River Bathymetry and Flow Conditions Downstream of the Spillway - The high river centered releases continued to move alluvial material downstream and toward both banks. The dive inspection found no indication that the riprap apron was affected by the test flow. Figure 10 gives the post test 2 river bathymetry and figure 11 shows the change in depth between test 1 and post test 2 conditions. By the end of test 2, the flow releases had cut channels toward each bank through the remaining alluvial deposit in the center of the river. The flow resulted in 4 to 6 ft of material deposition in the river downstream of bays 1, 2, 3, 4, and 11. River velocities measured during the test are given in figure 12. The large river center alluvial deposit continued to control flow patterns upstream of the fish screen bypass outfall. Similar to test 1, fishway flows were not distinguishable in the velocity measurements taken 100 ft downstream of the spillway endsill.

Figure 9 - Photographs of surface flow conditions during test 2.



View of white water turbulence downstream of gates 5, 6 and 7.



View of surface turbulence downstream of the left bank ladder.

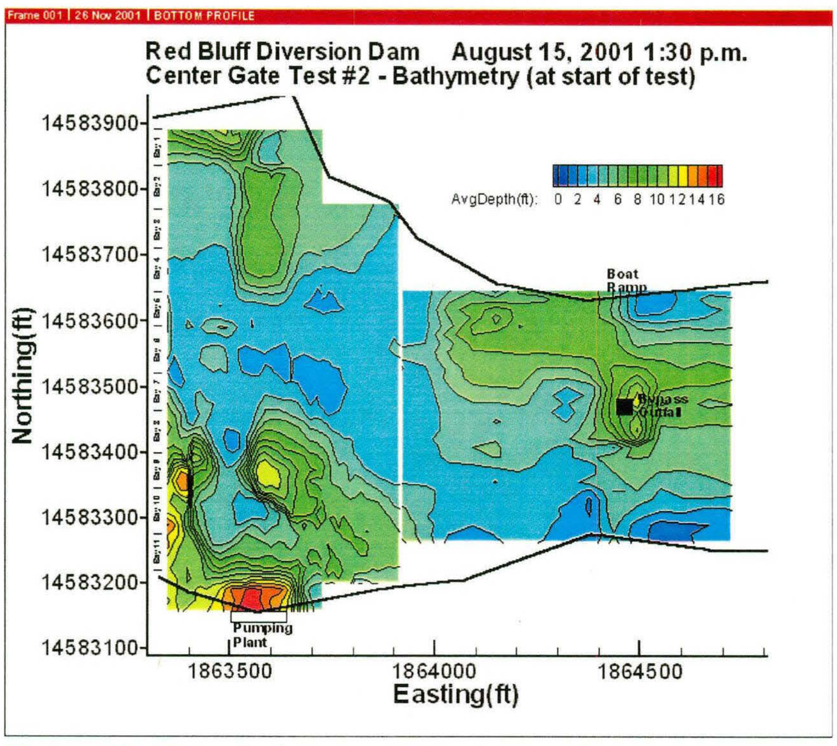


Figure 10 - River bathymetry following test 2.

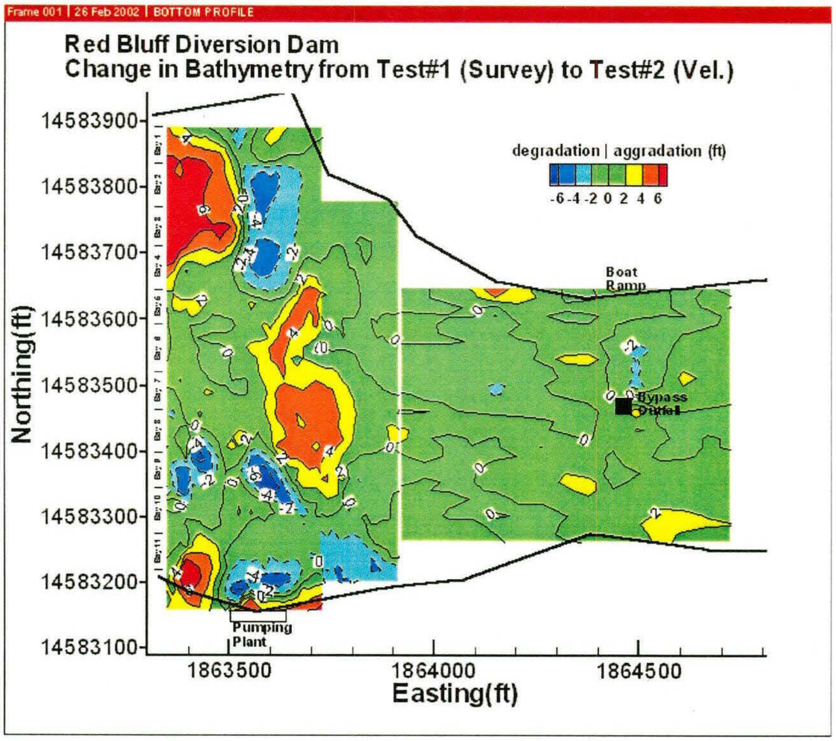


Figure 11 - Change in river bathymetry from test 1 to test 2.

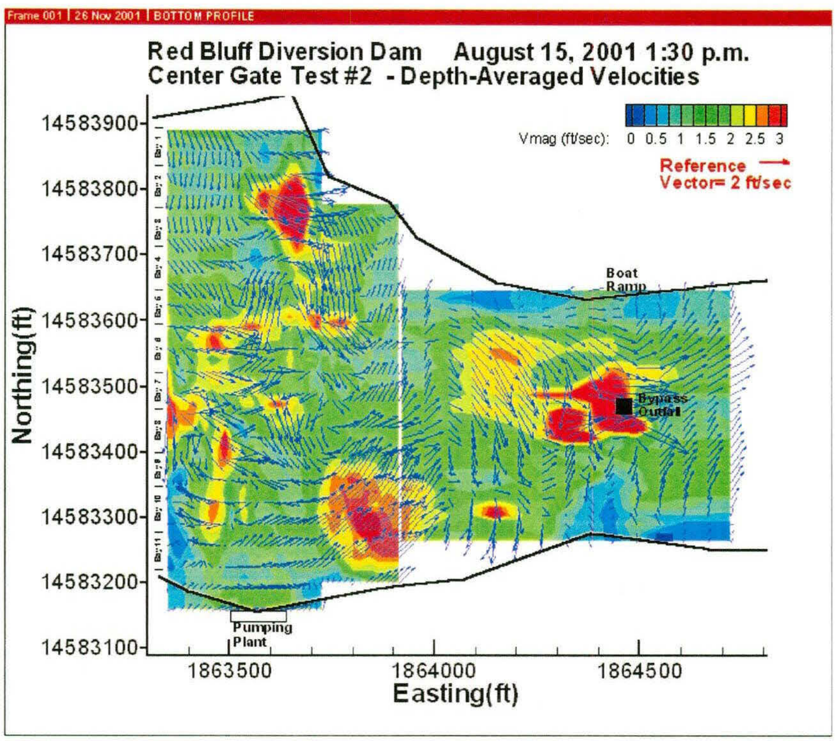


Figure 12 - Test 2 depth averaged velocities downstream of Red Bluff Diversion Dam.

River Center Spillway Release Test 3

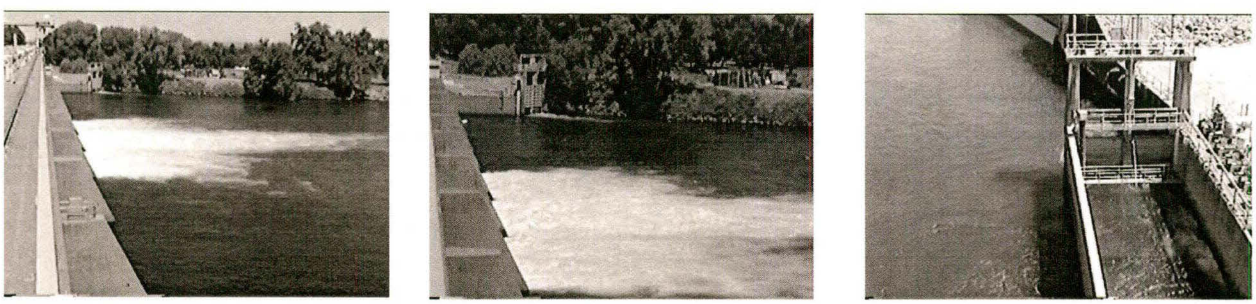
The objective of the third test was to concentrate all spillway flows to the center of the spillway with no sediment flushing flows from adjacent gates. For test 3, center releases were increased and gates 1, 2, 3, 4, 8, 9, 10, and 11 were closed. Gates 5, 6, and 7 were opened 1.7, 4.0 and 1.7 ft respectively, giving a 2.3 ft difference between adjacent gates (table 3).

Hydraulic Jump Stability - Releases from gates 5, 6, and 7 produced a bubble plume that extended well downstream of the spillway endsill, as shown in figure 13. The hydraulic jump downstream of gates 5, 6, and 7 remained stable. The flow through gate 6 yielded a ratio of tailwater depth to hydraulic jump conjugate depth of just under 1.0, (table 3).

Spillway Apron Abrasion Damage Potential - Following test 3, the amount of material deposited on the spillway apron roughly doubled. Refer to table 1of the Dive Report. New material was found in bays 4, 6, 7, 8, and 10. The greatest increase in material occurred in bay 8. All gravel deposits were again located immediately upstream of the spillway apron endsill.

River Bathymetry and Flow Conditions Downstream of the Spillway - The high river centered releases continued to move alluvial material downstream and toward both banks. Test 3 flows scoured a channel that extended about 800 ft downstream of the spillway (figure 14). Material removed during test 3 deposited downstream of bays 1 through 4 and 8 through 11 (figure 15). The dive inspection found no indication the riprap apron was affected by the test flow. River velocities measured during the test are given in figure 16. Similar to tests 1 and 2, fishway flows were not distinguishable in velocity measurements taken 100 ft downstream of the spillway endsill.

Figure 13 - Photographs of surface flow conditions during test 3.



View of white water turbulence downstream of gates 5, 6 and 7. Surface turbulence extended well downstream of the stilling basin endsill.

View of surface flow conditions exiting the left bank fishway.

View of surface flow conditions exiting the right bank fishway.

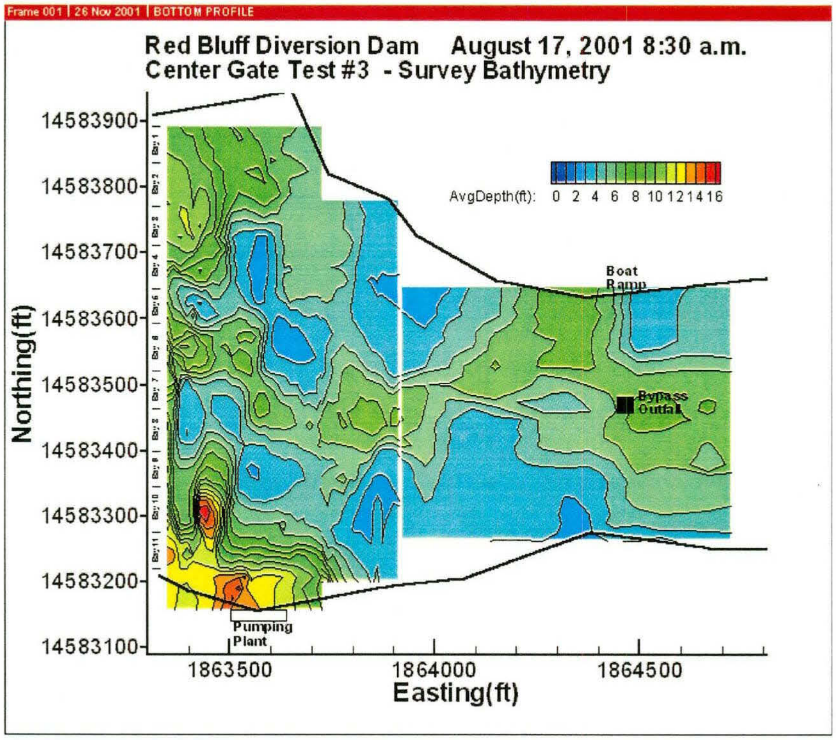


Figure 14 - River bathymetry following test 3.

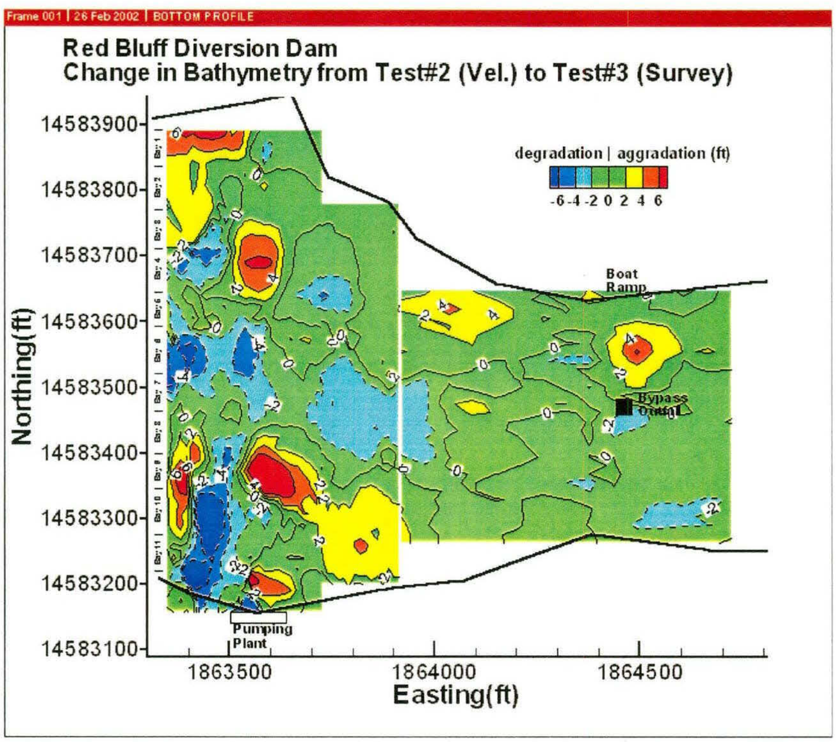


Figure 15 - Changes in river bathymetry from test 2 to test 3.

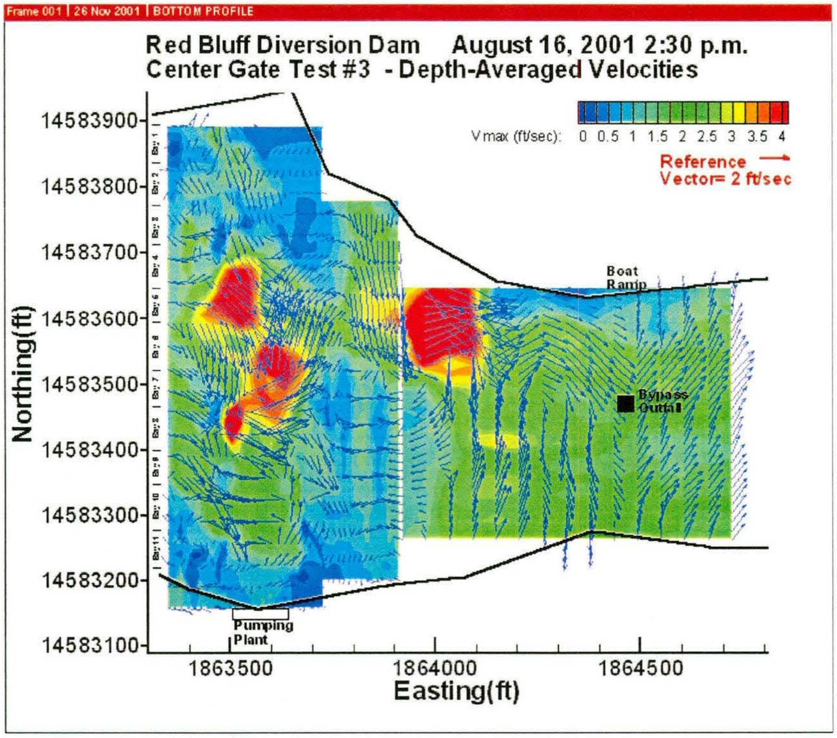


Figure 16 - Test 3 depth averaged velocities downstream of Red Bluff Diversion Dam.

Conclusions

The tests show the hydraulic jump downstream of the spillway gates is stable for conditions where the ratio of tailwater depth to hydraulic jump conjugate depth is 1.0 or greater. Low river flow conditions at the time of the testing did not allow testing tailwater depth to hydraulic jump conjugate depth ratios less than one. A value of 1.0 or greater is consistent with Reclamation Engineering Monograph 25 recommendations.

Exceeding a 1.0 ft differential gate opening between adjacent gates was not found to increase the potential for spillway apron abrasion for tests 1 and 2 where a flushing flow was provided adjacent to large gate openings. However, test 3 showed an increase in material moved upstream onto the spillway apron. Test 3 was unique in that spillway gate openings greater than 1 ft were used adjacent to closed gates. These tests indicate that spillway gate operation criteria can be relaxed to allow a differential gate opening of up to 2.0 ft between adjacent open gates if a 0.5 ft to 1.0 ft gate opening is maintained adjacent to a closed gate. The low river flow conditions at the time of the testing limited the range of non-symmetric gate operations that could be evaluated. Future tests during higher river flows would be required to evaluate adjacent gate openings of greater than 2 ft. Symmetric gate operation is recommended when fish attraction or sediment flushing is not required. Due to the limited extent of these tests, the spillway apron should be dive inspected and the criteria reevaluated after accumulating 6 months of operation with differential openings between adjacent gates of greater than 1.0 ft.

Between Red Bluff Diversion Dam and the Tehama Colusa Canal fish screen bypass outlet structure, river bathymetry and flow patterns vary greatly as a function of flow, sediment deposits, upstream bed load and spillway gate operation. The testing resulted in major changes in scour and redeposition patterns downstream of the dam. Flow patterns and depths measured in the downstream river are not necessarily indicative of future conditions resulting from spillway centered flow releases. However, the redistribution of river center deposits toward the river banks would be expected.

Table 1 - Spillway gate settings and hydraulic conditions during spillway Test No. 1

Test No.1

Sill Elevation 235.0 ft
Basin floor 228.00 ft

Reservoir elevation = 252.3 ft
Tailwater elevation = 239.8 ft

Gate No.	1	2	3	4	5	6	7	8	9	10	11 Sluice	Total Flow cfs
Opening, ft	0.25	0.50	0.50	0.50	1.25	2.40	1.25	0.50	0.50	0.25	0.50	
H1/b	69.2	34.6	34.6	34.6	13.8	7.2	13.8	34.6	34.6	69.2	34.6	
H2/b	19.1	9.5	9.5	9.5	3.8	2.0	3.8	9.5	9.5	19.1	9.5	
Cd	0.30	0.55	0.55	0.55	0.58	0.58	0.58	0.55	0.55	0.30	0.55	
Q/gate	148.9	545.9	545.9	545.9	1439.3	2763.5	1439.3	545.9	545.9	148.9	545.9	9216
Vel. gate, ft/s	14.2	26.0	26.0	26.0	27.4	27.4	27.4	26.0	26.0	14.2	26.0	
Endsill vel	2.0	5.1	5.1	5.1	8.5	11.7	8.5	5.1	5.1	2.0	5.1	
Fr1	5.0	6.5	6.5	6.5	4.3	3.1	4.3	6.5	6.5	5.0	6.5	
D2, ft	1.65	4.34	4.34	4.34	7.04	9.45	7.04	4.34	4.34	1.65	4.34	
TW(depth)/D2	7.15	2.71	2.71	2.71	1.67	1.25	1.67	2.71	2.71	7.15	2.71	

Table 2 - Spillway gate settings and hydraulic conditions during spillway Test No. 2

Test No. 2

Reservoir elevation = 252.5 ft
Tailwater elevation = 239.8 ft

Gate No.	1	2	3	4	5	6	7	8	9	10	11 Sluice	Total Flow cfs
Opening, ft	0.25	0.25	0.25	0.50	1.50	3.20	1.50	0.50	0.25	0.25	0.25	
H1/b	70.0	70.0	70.0	35.0	11.7	5.5	11.7	35.0	70.0	70.0	70.0	
H2/b	19.0	19.0	19.0	9.5	3.2	1.5	3.2	9.5	19.0	19.0	19.0	
Cd	0.30	0.30	0.30	0.56	0.56	0.58	0.56	0.56	0.30	0.30	0.30	
Q/gate	148.9	148.9	148.9	555.9	1667.6	3684.7	1667.6	555.9	148.9	148.9	148.9	9025
Vel.@gate, ft/s	14.2	14.2	14.2	26.5	26.5	27.4	26.5	26.5	14.2	14.2	14.2	
Vel. @ Endsill, ft/s	2.0	2.0	2.0	5.2	9.0	13.6	9.0	5.2	2.0	2.0	2.0	
Fr1	5.0	5.0	5.0	6.6	3.8	2.7	3.8	6.6	5.0	5.0	5.0	
D2, ft	1.65	1.65	1.65	4.42	7.36	10.73	7.36	4.42	1.65	1.65	1.65	
TW(depth)/D2	7.14	7.14	7.14	2.66	1.60	1.10	1.60	2.66	7.14	7.14	7.14	

Table 3 - Spillway gate settings and hydraulic conditions during spillway Test No. 3

Test No. 3

Reservoir elevation = 252.5 ft
Tailwater elevation = 239.7 ft

Gate No.	1	2	3	4	5	6	7	8	9	10	11 Sluice	Total Flow cfs
Opening, ft	0.00	0.00	0.00	0.00	1.70	4.00	1.70	0.00	0.00	0.00	0.00	
H1/b					10.2	4.3	10.2					
H2/b					2.8	1.2	2.8					
Cd					0.58	0.58	0.58					
Q/gate					1957.5	4605.8	1957.5					8521
Vel. gate					27.4	27.4	27.4					
Endsill vel					9:9	15.2	9.9					
Fr_1					3.7	2.4	3.7					
D2					8.10	11.81	8.10					
TW(depth)/D2					1.44	0.99	1.44					

Symbol definitions:

b - spillway gate opening
B - width of gates
Cd - spillway gate coefficient of discharge, $Q/(bB\sqrt{2gH1})$
D2 - hydraulic jump conjugate depth
Endsill vel. - estimated jet velocity at the stilling basin endsill
Fr_1 - Froude Number of the flow entering the stilling basin
H1 - head upstream of spillway gate referenced to the spillway crest
H2 - head downstream of spillway gate referenced to the spillway crest Q/gate - discharge per gate
Vel. gate - flow velocity through the gate opening
TW/D2 - ratio of tailwater depth to conjugate depth

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