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# PHYSICAL MODEL STUDY OF ENLARGED FISH LADDERS FOR RED BLUFF DIVERSION DAM

## RED BLUFF DIVERSION DAM FISH PASSAGE PROGRAM

September 1997

U.S. DEPARTMENT OF THE INTERIOR
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The Bureau of Reclamation, Water Resources Research Laboratory, conducted a physical model study to determine the potential of enlarged fish ladders to improve adult fish passage at Red Bluff Diversion Dam (RBDD). Ineffective fish passage at RBDD has been identified as a contributing factor in the decline of the anadramous fishery resource along the Sacramento River in California. This study was requested under the recently initiated Red Bluff Fish Passage Program (a combined effort of the Bureau of Reclamation, the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, and the California Department of Fish and Game). The results indicate that enlarged ladders have significant potential for generating improved near and far field attraction flow conditions in the diversion dam tailrace, compared with existing ladders. Furthermore, recommended diversion dam operating conditions associated with the proposed enlarged ladders have been identified. These results are intended for use in the development and implementation of solutions for improving fish passage at Red Bluff Diversion Dam.

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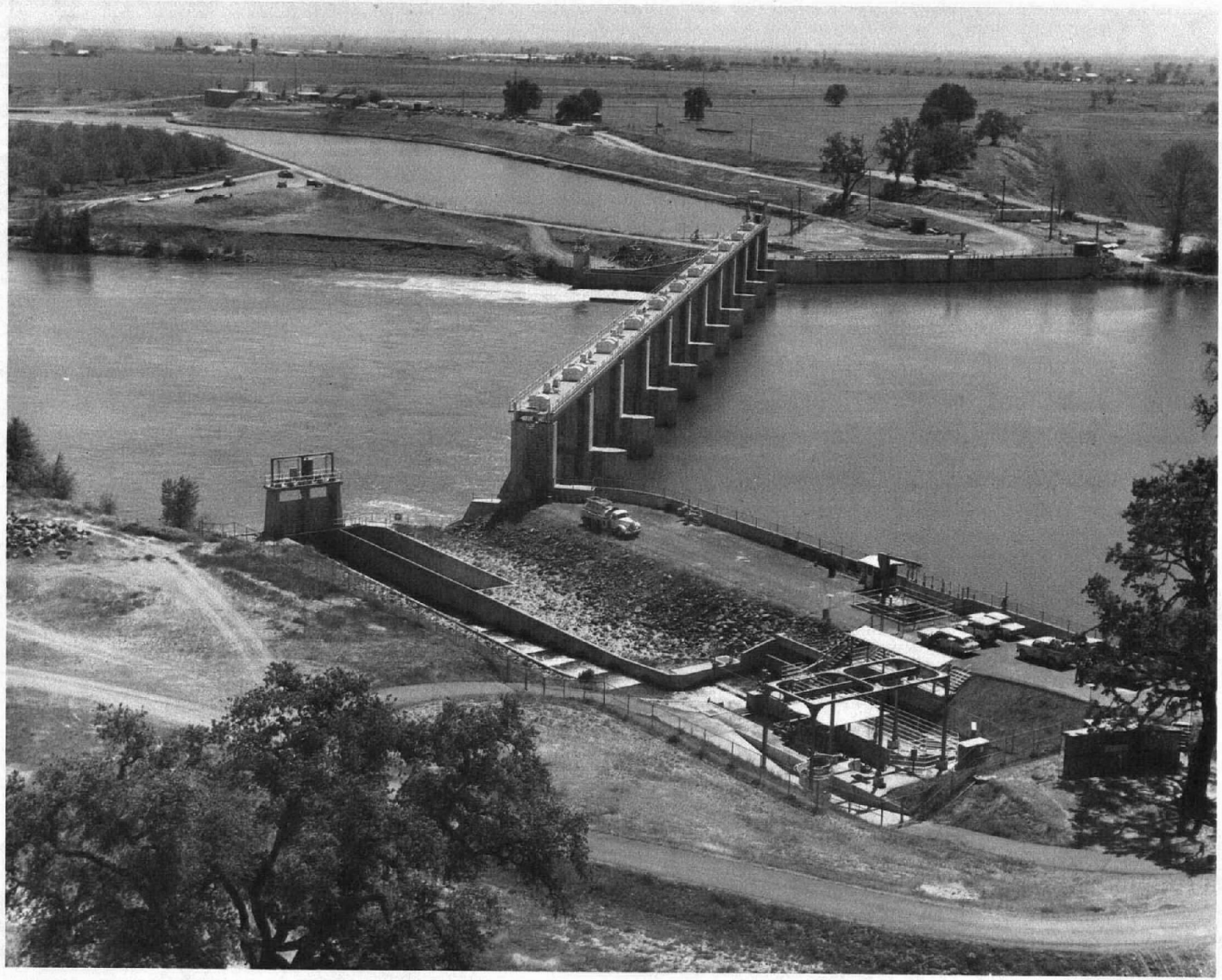

Aerial photograph of Red Bluff Diversion Dam and associated facilities.

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by

Joseph Kubitschek

Water Resources Research Laboratory
Water Resources Services
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Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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*U.S. Department of the Interior*
*Mission Statement*

The Mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to tribes.

# EXECUTIVE SUMMARY

## Introduction

A physical model study of enlarged fish ladders for Red Bluff Diversion Dam (RBDD) was conducted at the Bureau of Reclamation (Reclamation) Water Resources Research Laboratory in Denver, Colorado. A 1:36 scale model of the diversion dam, associated fish passage facilities, and a 900-ft reach of tailrace topography was used to investigate the potential for enlarged ladders to improve adult fish passage at RBDD. The enlarged ladder configurations which were evaluated include: (1) replacement of the existing right abutment 320-$ft^3/s$ fish ladder with a larger 800-$ft^3/s$ ladder; (2) replacement of the existing left abutment 320-$ft^3/s$ fish ladder with a larger 1,000-$ft^3/s$ ladder; and, (3) construction of a new 1,000-$ft^3/s$ center fish ladder to be installed in place of gate No. 6 at the diversion dam. The scope of this study consisted of evaluating the proposed enlarged ladder release interactions with the tailrace velocity field generated by various RBDD gate setting configurations during the typical gates down period (May 15 through September 15). Ladder internal hydraulic details were not modeled because these details do not influence ladder release interactions in the tailrace velocity field. However, ladder release discharges and corresponding entrance geometries were modeled consistent with conventional ladder designs and resource agency velocity criteria.

The results of this study provide information regarding the performance potential of enlarged ladders in conjunction with various RBDD gate operations. Likewise, these results provide an indication of those RBDD operating configurations which appear to have pitfalls. However, should enlarged ladders be designed and implemented, the appropriate degree of flexibility in ladder entrance locations will be required to accommodate the range of possible fish staging locations with respect to the range of required adjacent gate settings.

## Conclusions

- The enlarged ladder alternative demonstrates significant potential for improving adult fish passage at RBDD by generating improved near and far field attraction flow conditions in the tailrace for the range of Lake Red Bluff release conditions tested.

- Near and far field attraction flow performance of the enlarged ladder alternative is influenced by RBDD spillway gate operation, ladder size, ladder entrance location, and ladder entrance orientation.

- For low end Lake Red Bluff releases (i.e., 5,000 to 10,000 $ft^3/s$) spillway gates adjacent to ladder entrances should be operated to pass river flows which are not diverted or passed through fish ladders. Such an approach to RBDD operation serves the primary purpose of positioning fish staging near ladder entrances and the secondary purpose of supplementing ladder releases for attraction.

- For mid-range Lake Red Bluff releases (i.e., 10,000 to 15,000 $ft^3/s$), spillway gate releases have a significant impact on the tailrace velocity field because ladder releases comprise a smaller percentage of the total Lake Red Bluff release compared with low end release conditions. In this case, the adjacent gate or the crowning flow approach to RBDD operation may be used to provide favorable attraction to ladder entrances. Again, spillway gates adjacent to ladder entrances should be operated to position fish staging locations near ladder entrances.

- For high end Lake Red Bluff release conditions (i.e., 15,000 to 20,000 $ft^3/s$ and above), spillway releases dominate the tailrace velocity field. In this case, the most favorable attraction flow conditions are achieved using the crowning flow approach to RBDD gate operation. This approach takes advantage of fish behavior to provide guidance to ladder entrances. For these conditions, the enlarged ladders produce favorable near field attraction flow features.

- The ladder sizes (discharges) identified for the enlarged ladder alternative appear to be the most practical for the range of Lake Red Bluff release conditions tested based on historic hydrologic data. For Lake Red Bluff release conditions greater than 20,000 $ft^3/s$, adult passage will still be achievable with the use of enlarged ladder sizes identified during this study. However, efficiency is expected to decrease as Lake Red Bluff releases increase above this point. Although larger ladder sizes may be desirable to produce improved attraction flow performance for Lake Red Bluff releases higher than 20,000 $ft^3/s$, such designs are not likely practical from an engineering standpoint.

- Ladder entrance locations and orientations have a moderate influence on near and far field attraction flow performance, which depends on spillway gate operation adjacent to ladder entrances. Thus, selection of appropriate ladder entrance locations and orientations should be based on adjacent gate release-generated fish staging locations.

**Recommendations**

- Based upon the results of this study, the enlarged ladder alternative has significant potential for improving adult fish passage at RBDD and is recommended for further development and implementation.

- The appropriate ladder entrance locations and orientations should be selected consistent with likely fish staging locations as a function of adjacent gate settings. Thus, sufficient flexibility for field investigation and refinement of performance is recommended for the final design.

- Based on the results of this study, it is recommended that spillway releases for low end Lake Red Bluff release conditions (i.e., 5,000 to 10,000 $ft^3/s$) be made through gates adjacent to ladder entrances in order to position fish staging locations near ladder entrances and to supplement far field attraction flow features. For mid-range Lake Red Bluff releases (i.e., 10,000 to 15,000 $ft^3/s$), spillway releases may be made through adjacent gates or by using the crowning flow approach. This range represents the transitional range between the adjacent gate and crowning flow operational strategies. In either case, false or dead end attractions should be avoided. For high end Lake Red Bluff release conditions (i.e., 15,000 to 20,000 $ft^3$ and above), the fully crowned approach is recommended to pass river flows while maintaining strong far field attraction flow and guidance features. To achieve this condition, gate settings should be tapered with successively higher spillway releases through gates which are located successively farther from ladder entrances. In this manner, the tapering hydraulic barrier may be used to take advantage of behavior and guide fish toward ladder entrances.

- Finally, additional field studies are recommended prior to final design and implementation of enlarged ladders. Such studies would include radio tagging investigations to improve the level of certainty regarding fish staging locations with respect to RBDD spillway gate operating configurations. The results would be used to identify the range of ladder entrance locations required to accommodate the likely range of fish staging locations.

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## PURPOSE

Under the Red Bluff Fish Passage Program, this physical model study was conducted to determine the potential for enlarged fish ladders to improve adult fish passage at Red Bluff Diversion Dam (RBDD). The results are also intended to provide guidance in selection of appropriate ladder sizes, design information, and identification of RBDD operating configurations in conjunction with enlarged ladders, which demonstrate the greatest potential for efficient adult fish passage from an attraction flow standpoint.

## APPLICATION

The results of this study address adult fish passage issues specifically related to RBDD and associated operational and hydraulic characteristics. These results provide information which is intended to guide the Interagency Fisheries Work Group (IFWG) in the development and implementation of solutions for improving adult passage at RBDD. As such, details related to optimum ladder sizes, ladder entrance locations and orientations, and RBDD operating configurations have been determined. However, these results also provide insight into general hydraulic features associated with fish ladder and spillway release interactions. In this respect, the potential for broad application exists.

## INTRODUCTION

Red Bluff Diversion Dam is located on the Sacramento River about 2 miles southeast of Red Bluff, California. Figure 1 is a general location map which identifies project location. The diversion dam is a multiple gate concrete weir structure which is 54 ft high and 720 ft wide. Lake Red Bluff, which is created by RBDD, is about 3 miles long and has a storage capacity of 3,900 acre-ft under normal water surface elevations and operating conditions. Figure 2 represents plan and elevation details for the diversion dam and appurtenances. The purpose of the project is to divert Sacramento River water to the west side of the river valley for irrigation via the Tehama-Colusa and Corning Canals.

The existing fish passage facilities at RBDD consist of two primary fish ladders and a secondary center ladder. The primary fish ladders are located at the right and left abutments of the diversion dam. These ladders are similar in design with the exceptions that the left abutment ladder contains a fish trap and evaluation facilities and has a different entrance orientation. The right abutment ladder entrance orientation is located downstream and parallel to the RBDD tailrace. In contrast, the left abutment ladder entrance orientation is 45-degrees downstream with respect to the tailrace. Figure 3 represents plan and elevation details for the right abutment fish ladder. Both ladders are sized for 85-$ft^3/s$ pool to pool discharges with about 235-$ft^3/s$ supplemental flow discharges. The supplemental flows are introduced into the downstream portion of the fish ladders via four diffusers located along the right walls of each ladder. The center fish ladder is temporary. It is installed and removed at the beginning and end of each irrigation season (i.e., gates down period from May 15 to September 15), respectively. Limited design and operational information is available regarding pool to pool and supplemental flow discharges for the existing center ladder.

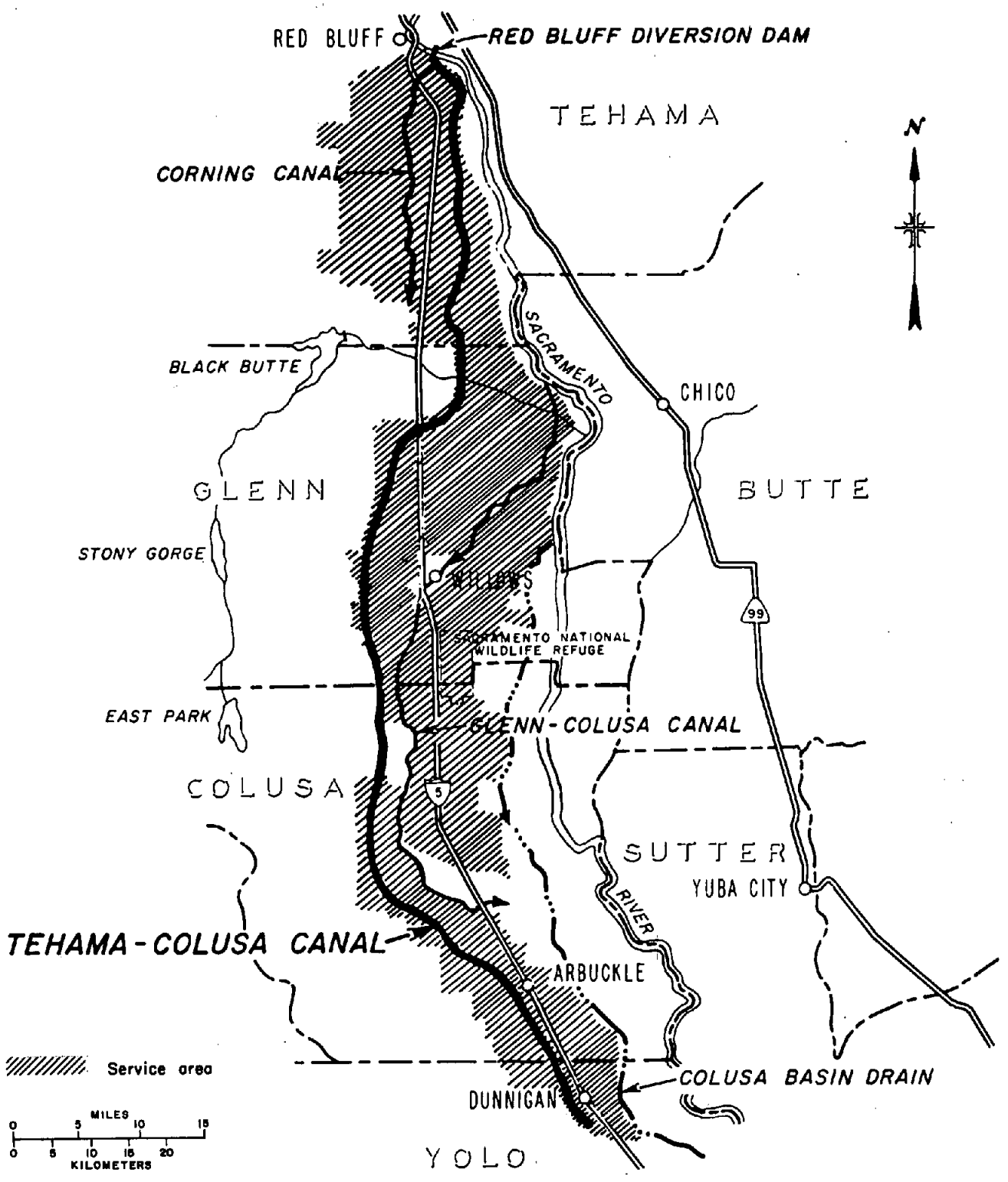


Figure 1. - General location map of Red Bluff Diversion Dam.

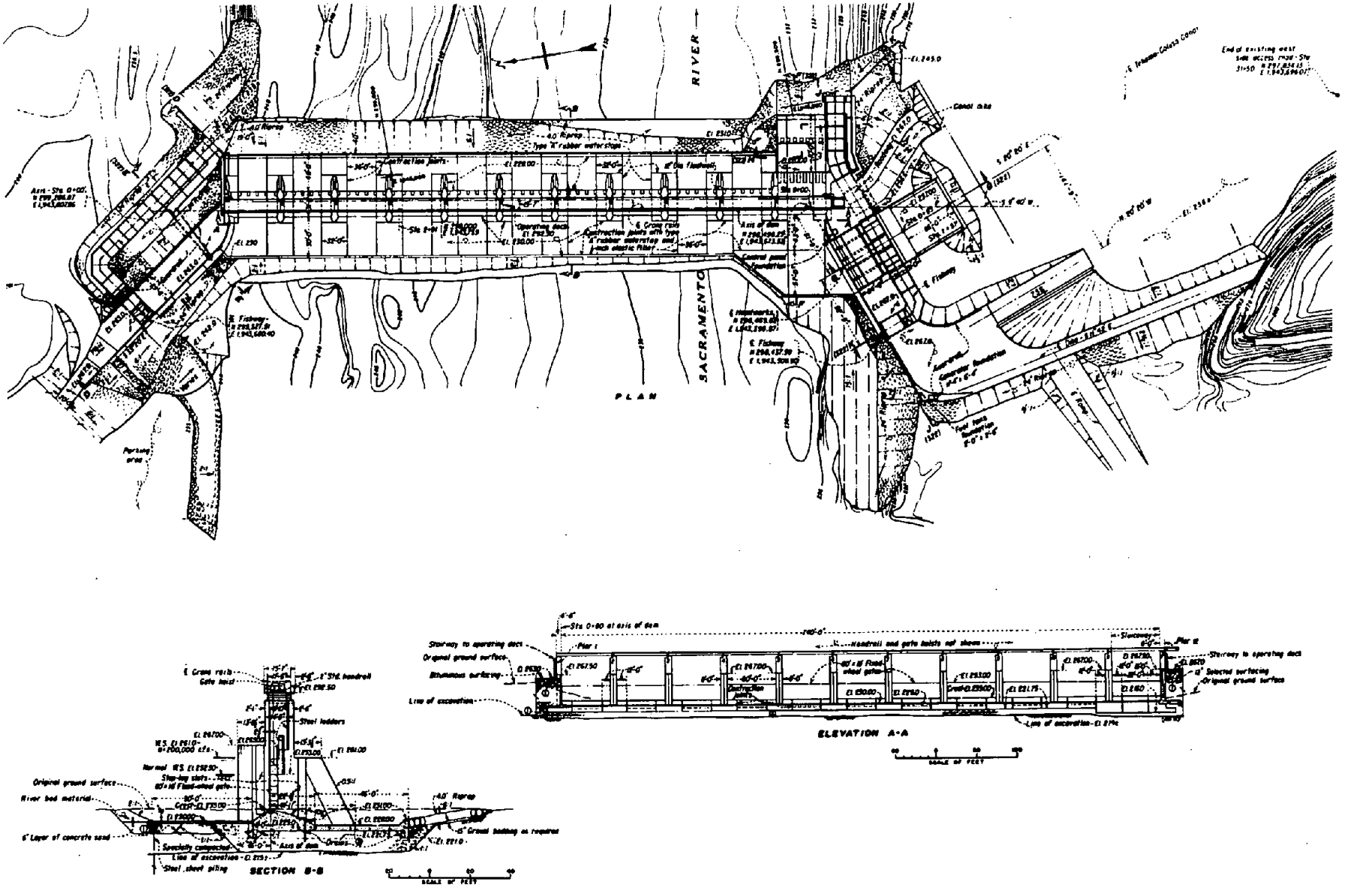


Figure 2. - Plan and elevation details for Red Bluff Diversion Dam.

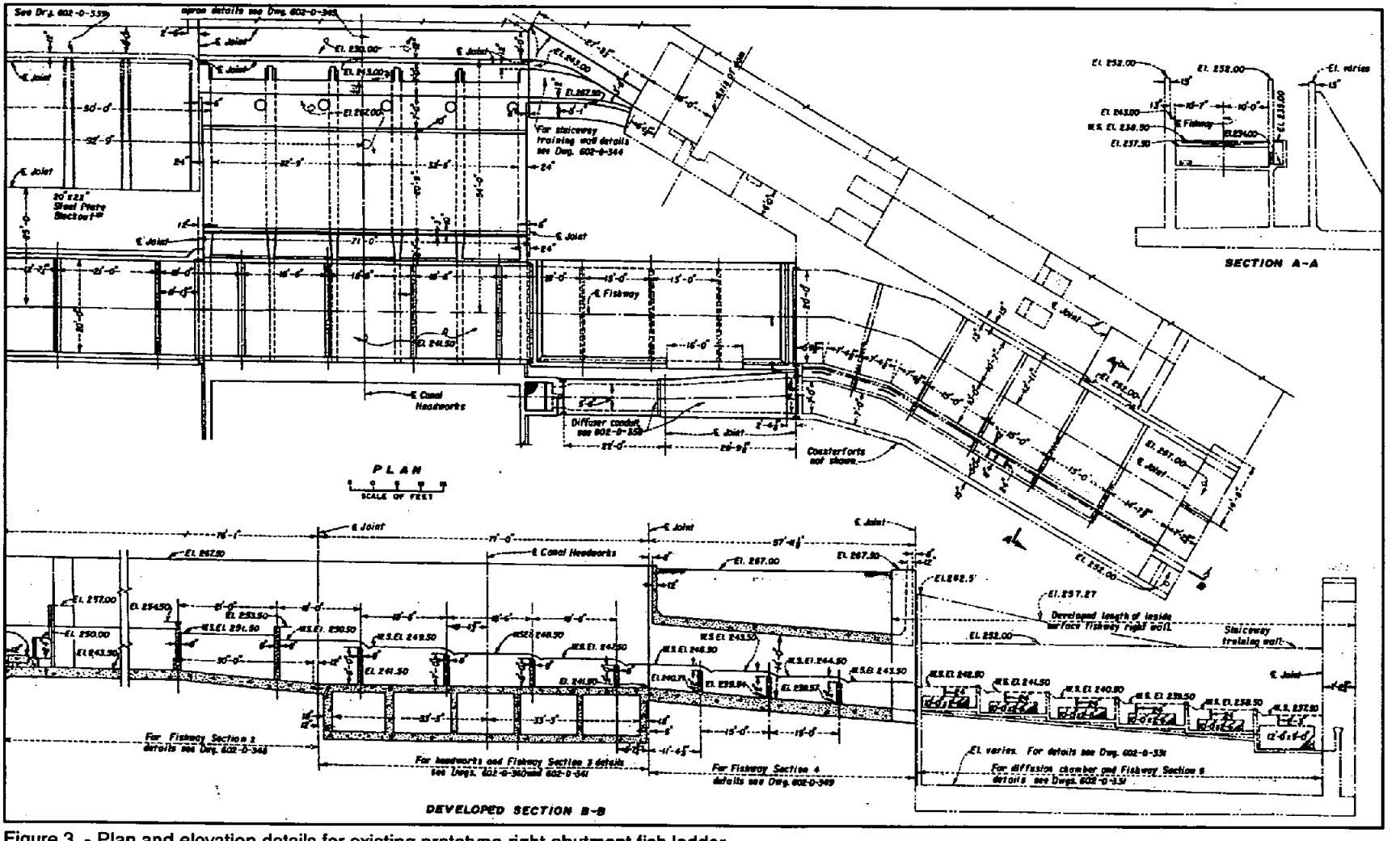


Figure 3. - Plan and elevation details for existing prototype right abutment fish ladder.

### Background

Inadequate fish passage at RBDD has been identified as a factor in the decline of the anadromous fishery resource (primarily salmon and steelhead) along the Sacramento River. In response to this decline, the Red Bluff Fish Passage Program was initiated to identify, develop, and implement long term solutions for improving fish passage. This program is a combined effort of the Bureau of Reclamation (Reclamation), the U.S. Fish and Wildlife Service (F&WS), the National Marine Fisheries Service (NMFS), and the California Department of Fish and Game (CDF&G). During the initial stages of the program, an appraisal report (Reclamation, 1991) was published, which identifies program direction and alternatives for improving fish passage at RBDD. One alternative, replacement of existing fish ladders with larger ladders, was selected among others for further development. This alternative includes replacement of the existing right abutment 320-$ft^3/s$ fish ladder with a larger 800-$ft^3/s$ ladder; replacement of the existing left abutment 320-$ft^3/s$ fish ladder with a larger 1,000-$ft^3/s$ ladder; and construction of a new 1,000-$ft^3/s$ center fish ladder to be installed in place of gate No. 6 at the diversion dam. It is felt that adult fish passage at RBDD can be improved with the enlarged ladder alternative by creating improved attraction flow in the downstream tailrace pool. Such conditions would allow fish to efficiently sense and locate ladder entrances, thus minimizing passage delays. To determine the potential of enlarged ladders to improve adult fish passage at RBDD, Reclamation's Water Resources Research Laboratory (WRRL) was tasked with conducting a physical model study.

### Problem Statement

One of the primary issues associated with adult fish passage at RBDD involves fish ladder attraction flow conditions in the diversion dam tailrace. Given existing fish ladder sizes, limited discharge capacity exists for providing strong attraction flow features over the full range of potential Lake Red Bluff release conditions encountered during the typical gates down period. During this time, RBDD provides diversions to the Tehama-Colusa and Corning Canals and is considered a barrier to adult fish passage.

## CONCLUSIONS

- The enlarged ladder alternative demonstrates significant potential for improving adult fish passage at RBDD by generating improved near and far field attraction flow conditions in the tailrace, compared with existing ladders, for the range of Lake Red Bluff release conditions tested.

- Near and far field attraction flow performance of the enlarged ladder alternative is influenced by RBDD spillway gate operation, ladder size, ladder entrance location, and ladder entrance orientation.

- For low end Lake Red Bluff releases (i.e., 5,000 to 10,000 $ft^3/s$), spillway gates adjacent to ladder entrances should be operated to pass river flows which are not diverted or passed through fish ladders. Such an approach to RBDD operation serves the primary purpose of positioning fish staging near ladder entrances and the secondary purpose of supplementing ladder releases for attraction.

- For mid-range Lake Red Bluff releases (i.e., 10,000 to 15,000 $ft^3/s$), spillway gate releases have a significant impact on the tailrace velocity field because ladder releases comprise a smaller percentage of the total Lake Red Bluff release compared with low end release conditions. In this case, the adjacent gate or the crowning flow approach to RBDD operation may be used to provide favorable attraction to ladder entrances. Again, spillway gates adjacent to ladder entrances should be operated to position fish staging locations near ladder entrances.

- For high end Lake Red Bluff release conditions (i.e., 15,000 to 20,000 $ft^3/s$ and above), spillway releases dominate the tailrace velocity field. In this case, the most favorable attraction flow conditions are achieved using the crowning flow approach to RBDD gate operation. This approach takes advantage of fish behavior to provide guidance to ladder entrances. For these conditions, the enlarged ladders produce favorable near field attraction flow features.

- The ladder sizes (discharges) identified for the enlarged ladder alternative appear to be the most practical for the range of Lake Red Bluff release conditions tested based on historic hydrologic data. For Lake Red Bluff release conditions greater than 20,000 $ft^3/s$, adult passage will still be achievable with the use of enlarged ladder sizes identified during this study. However, efficiency is expected to decrease with the increase of Lake Red Bluff releases above this point. Although larger ladder sizes may be desirable to produce improved attraction flow performance for Lake Red Bluff releases higher than 20,000 $ft^3/s$, such designs are not likely practical from an engineering standpoint.

- Ladder entrance locations and orientations have a moderate influence on near and far field attraction flow performance which depends on spillway gate operation adjacent to ladder entrances. Thus, selection of appropriate ladder entrance locations and orientations should be based on adjacent gate release-generated fish staging locations.

## PHYSICAL MODEL

The physical model of RBDD and associated fish passage facilities was constructed at Reclamation's Water Resources Research Laboratory in Denver, Colorado. Figure 4 is a plan view schematic of the physical model. Figure 5 is a photograph of the physical model. A 1:36 scale was selected such that the entire diversion dam width and a 900-ft reach of tailrace topography could be investigated.

Ladder entrance geometries were modeled consistent with resource agency velocity criteria, which require 8.0- to 10.0-ft/s velocities exiting the fish ladders. These velocity criteria have been established to provide attraction to ladder entrances. Internal ladder details were not modeled because they do not influence tailrace attraction flow features. Thus, only ladder entrance conditions (i.e., size and discharge) need to be modeled to determine the downstream influence on diversion dam tailrace velocity field patterns.

### Similitude

The physical model of RBDD and associated fish passage facilities must be geometrically and kinematically similar to the prototype for accurate prediction of prototype performance under specific operating conditions. Similitude is achieved by maintaining a Froude number for the

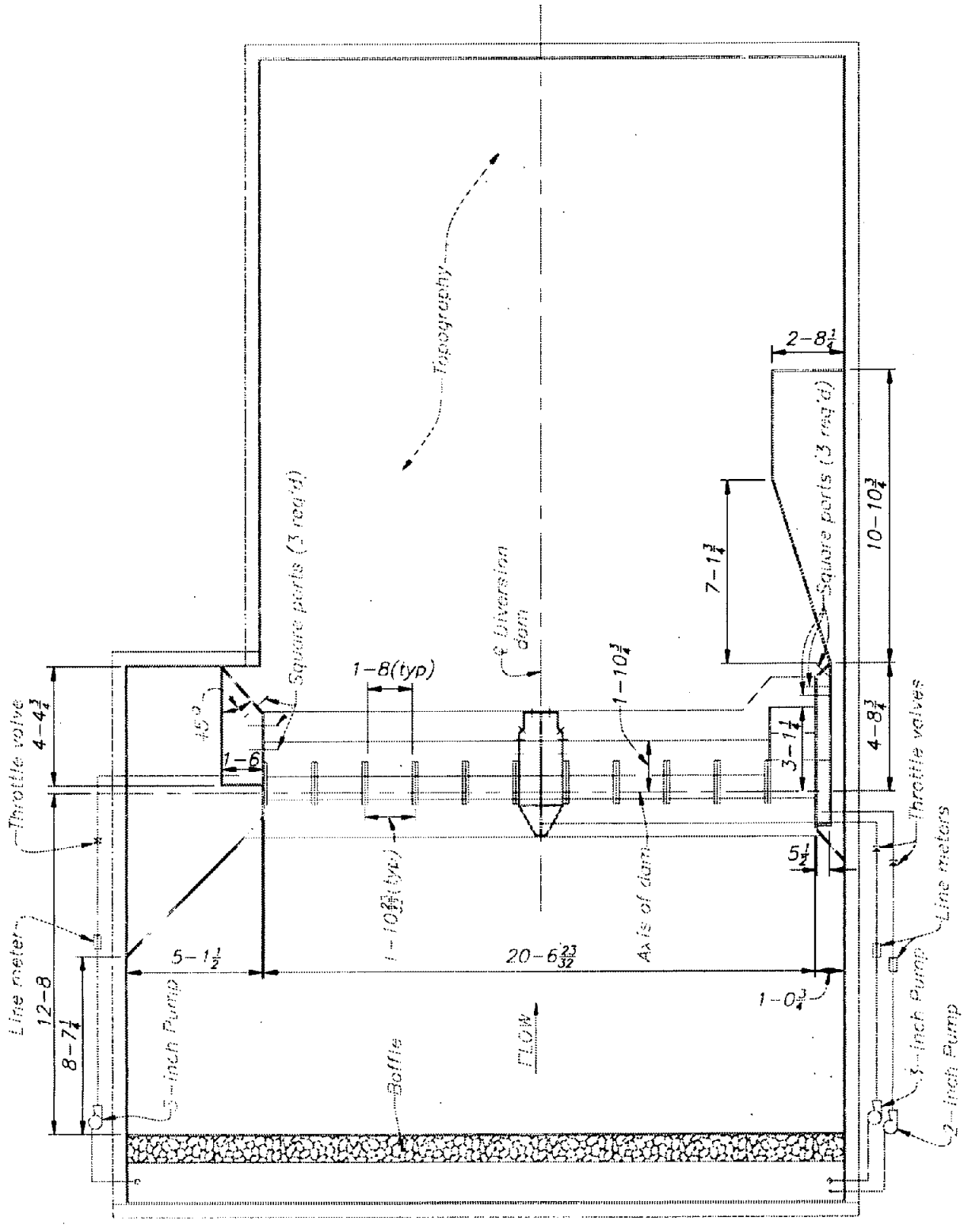


**Figure 4. - Plan view schematic of 1:36 scale physical model as constructed in the laboratory.**

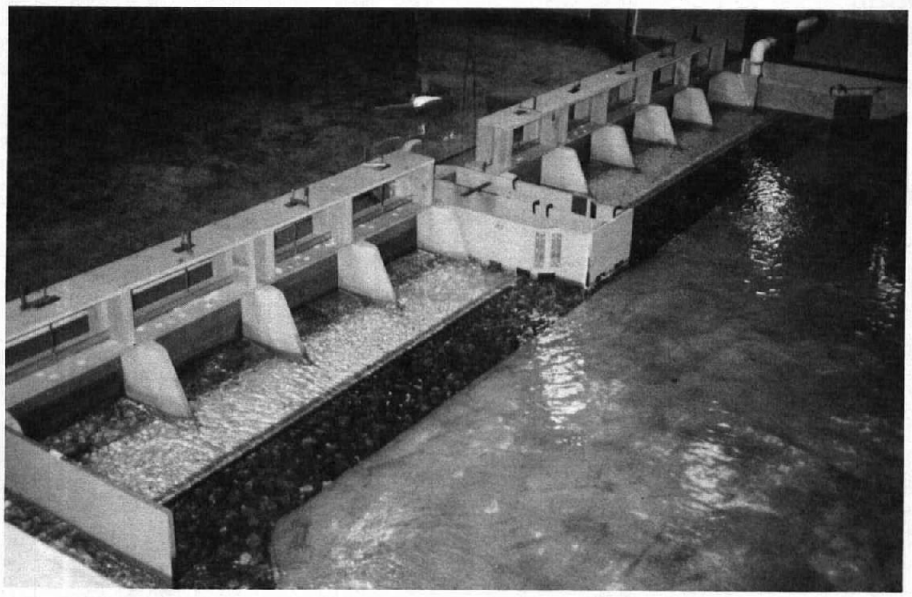

Figure 5. - Photograph of physical model as constructed in the laboratory.

physical model equal to that of the prototype for all hydraulic conditions tested. The Froude number represents the ratio of inertial forces to gravitational forces throughout a particular flow field. This similitude criterion was selected because gravitational forces predominate for a physical model of this type. The Froude number is defined as:

$$Fr = \frac{u}{\sqrt{(gL)}}$$

where:

$u$ = characteristic velocity
$g$ = gravitational acceleration
$L$ = characteristic length

Geometric similarity is achieved with the ratios of all geometric parameters between model and prototype being equal. This similarity is represented by the length ratio:

$$L_r = \frac{L_m}{L_p}$$

where:

$L_m$ = model characteristic length
$L_p$ = prototype characteristic length

Kinematic similarity is achieved with the ratios of all model to prototype velocities being equal. The following scale relationships are determined based upon Froude number similitude:

***Geometric***

Length ratio: $L_r = 1{:}36$
Area ratio: $A_r = (L_r)^2 = 1{:}1{,}296$
Volume ratio: $V_r = (L_r)^3 = 1{:}46{,}656$

***Kinematic***

Time ratio: $t_r = (L_r)^{1/2} = 1{:}6$
Velocity ratio: $u_r = (L_r)^{1/2} = 1{:}6$
Acceleration ratio: $a_r = 1{:}1$
Discharge ratio: $Q_r = (L_r)^{5/2} = 1{:}7{,}776$

The physical model tailrace topography represents an approximation of prototype tailrace topography. Prototype tailrace topography changes frequently, which prevents modeling for all cases. However, the model tailrace topography represents a close approximation to that of the prototype. Because existing prototype ladder configurations were modeled to provide baseline data for comparison with the proposed enlarged ladder configurations, a sound basis exists for a qualitative comparison of the potential for enlarged ladders to improve attraction flow conditions over existing ladders and consequently improve adult fish passage.

**Methods and Testing**

Physical model tailrace velocity field data were acquired using a 35-mm camera mounted on an overhead gantry crane. The tailrace was sectioned into four quadrants. The flow in each quadrant was seeded with 1-in-diameter paper confetti. Photographs were taken with an extended shutter time setting of 1.0 second. This time setting and corresponding photograph of the seeded flow field produced streak lines from which surface velocities were determined. Figure 6 represents a typical photograph acquired using this procedure. Photographs were overlaid on an AutoCAD digitizing tablet. Start and end points of streak lines were digitized using the stylus. Velocity vectors were determined by measuring streak length and using the known 1.0-second photographic exposure time. This determination was achieved automatically during the digitizing process with an AutoCAD LISP routine written for this purpose. Figure 7 is a typical data results plot generated using this procedure. The information contained on figure 7 is a combination of data acquired for all four quadrants of the diversion dam tailrace for specific operating conditions. This plot contains information regarding the spatial location, magnitude, and direction of the velocity vector field data acquired during testing.

Preliminary testing was completed in 1995 and included evaluation of proposed enlarged ladder performance for a range of Lake Red Bluff releases under uniform gate settings. Each ladder was tested separately to establish baseline ladder release interactions with the diversion dam tailrace velocity field. Three ladder entrance locations were tested for each ladder to establish the influence of ladder entrance location on attraction flow performance. Table 1 represents test conditions for preliminary investigations. Table 2 consists of corresponding gate settings required to pass spillway releases. The total Lake Red Bluff release is defined in this study as the total discharge passing RBDD, which includes both ladder and spillway gate releases.

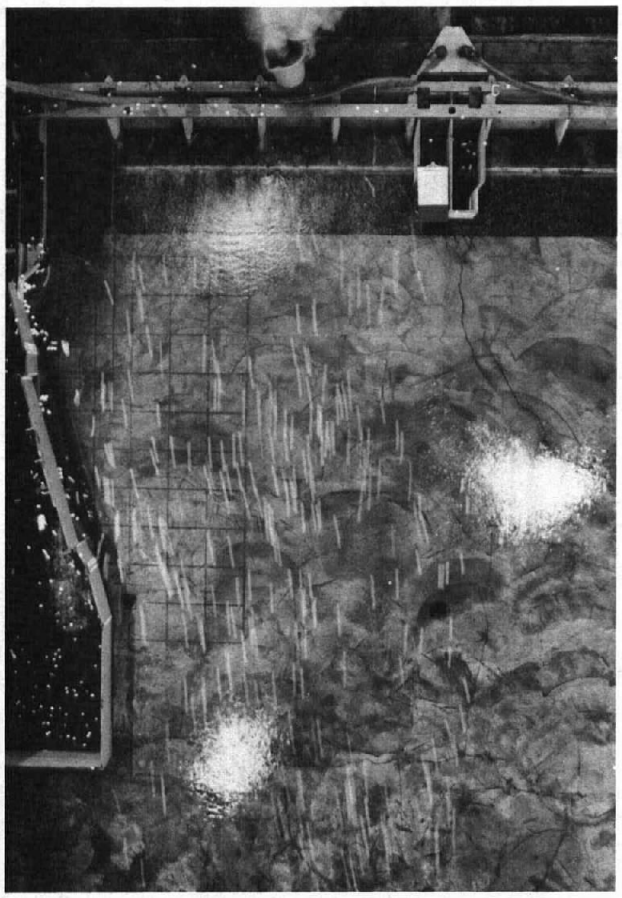

Figure 6. - Typical data acquisition photograph. Streak lines generated by 1-second exposure time.

Testing was resumed in 1996 for the completion of this study. The scope of work included evaluating the enlarged ladder configurations in combination over the full range of Lake Red Bluff release conditions expected during a typical irrigation season or gates down period. Based upon an analysis of historic hydrologic data, Lake Red Bluff release test conditions of 5,000, 10,000, 15,000, and 20,000 $ft^3/s$ were selected. The results of the historic hydrologic data analysis have been presented as figures 8 and 9. Figure 8 represents Lake Red Bluff release discharge versus percent of time equaled or exceeded and supports selected Lake Red Bluff release test points. Figure 9 represents Lake Red Bluff release discharge versus time for the gates down period of record from 1976 to 1994. Initially, testing was conducted under uniform gate settings for all three proposed enlarged ladders to provide continuity with preliminary investigations. In this case, Lake Red Bluff total release test points were selected consistent with those of the preliminary testing. These test points included total Lake Red Bluff releases of 4,000, 11,000, 19,000, and 39,000 $ft^3/s$. Table 3 identifies these initial test conditions for this initial phase of final testing. Table 4 identifies those uniform gate settings corresponding with initial testing for these final investigations.

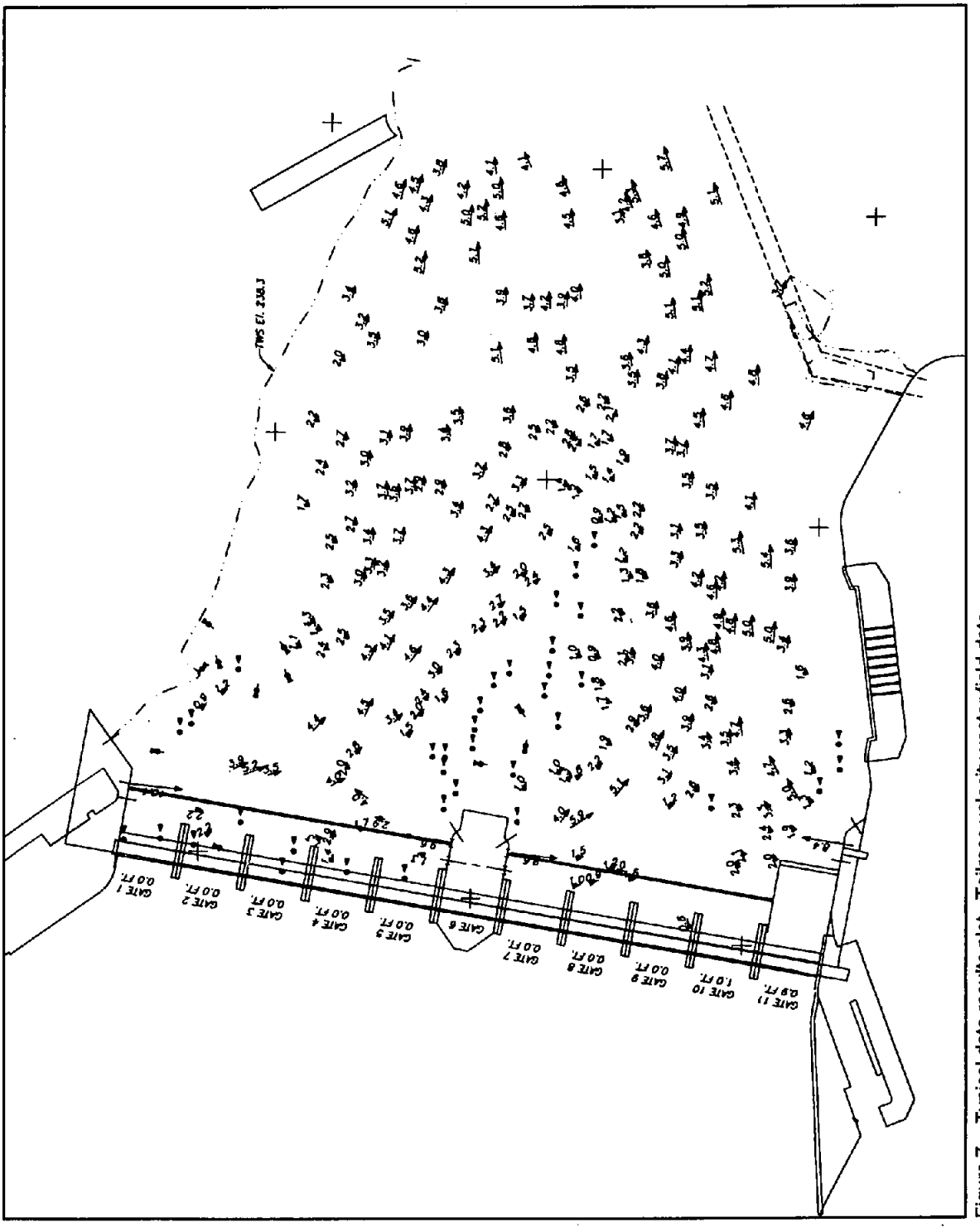


Figure 7. - Typical data results plot. Tailrace velocity vector field data.

Table 1. - Preliminary testing: individual ladders tested separately with uniform gate settings.

| Proposed Ladder | Ladder Release ($ft^3/s$) | Gate Release ($ft^3/s$) | Lake Red Bluff Release ($ft^3/s$) | Lake Red Bluff w.s.el.* (ft) | t.w.el. (ft) |
|---|---|---|---|---|---|
| Right bank | 800 | 1,400 | 2,200 | 252.5 | 238.0 |
| | | 8,400 | 9,200 | | 239.6 |
| | | 16,400 | 17,200 | | 241.8 |
| | | 36,400 | 37,200 | | 245.0 |
| Center | 1,000 | 1,200 | 2,200 | 252.5 | 238.0 |
| | | 8,200 | 9,200 | | 239.6 |
| | | 16,200 | 17,200 | | 241.8 |
| | | 36,200 | 37,200 | | 245.0 |
| Left bank | 1,000 | 1,200 | 2,200 | 252.5 | 238.0 |
| | | 8,200 | 9,200 | | 239.6 |
| | | 16,200 | 17,200 | | 241.8 |
| | | 36,200 | 37,200 | | 245.0 |
| Left bank | 3,000 | 0 | 3,000 | 252.5 | 238.5 |
| | | 6,200 | 9,200 | | 239.6 |
| | | 14,200 | 17,200 | | 241.8 |
| | | 34,200 | 37,200 | | 245.0 |

*water surface elevation

Following the initial testing, the proposed enlarged ladder configurations were tested simultaneously for those release condition test points selected based upon historic hydrologic data. The test points are given in table 5. Corresponding gate settings have been included in table 6 for each Lake Red Bluff release condition and corresponding RBDD operational configurations. Again, the Lake Red Bluff release column consists of combined spillway and fish ladder releases and represents total Lake Red Bluff releases. Finally, existing ladder configuration were tested for conditions identical to total Lake Red Bluff release hydraulic set points identified in table 5. Table 7 represents gate settings associated with this testing and consists of historically documented field gate settings based on RBDD daily operation logs. All testing for these final investigations has been identified as series Nos. 1 through 4. For each series, various tests are identified which represent tested ladder entrance locations for the respective Lake Red Bluff release conditions and corresponding gate setting configurations. Series No. 1 testing represents uniform gate settings for enlarged ladder concepts operated simultaneously (tables 3 and 4). Series Nos. 2 and 3 testing represents a variety of non-uniform gate setting operations of RBDD for enlarged ladder concepts (tables 5 and 6). Series No. 4 testing represents existing prototype ladder configurations operated for documented RBDD field gate settings (table 7).

Table 2. - Uniform gate settings for preliminary investigations.

| Spillway Release ($ft^3/s$) | | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rt. bank(800 $ft^3/s$ ) | 1,400 | 1.1 | - | - | - | - | - | - | - | - | - | - |
| | 8,400 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| | 16,400 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| | 36,400 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| Center(1,000 $ft^3/s$ ) | 1,200 | 1.0 | - | - | - | - | - | - | - | - | - | - |
| | 8,200 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| | 16,200 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| | 36,200 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| Lf. bank(1,000 $ft^3/s$) | 1,200 | 1.0 | - | - | - | - | - | - | - | - | - | - |
| | 8,200 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| | 16,200 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| | 36,200 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| Lf. bank(3,000 $ft^3/s$) | 0 | - | - | - | - | - | - | - | - | - | - | - |
| | 6,200 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 14,200 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| | 34,200 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |

Table 3. - Final investigations— initial testing: proposed enlarged ladders operated simultaneously for uniform gate settings consistent with Lake Red Bluff releases of table 2 (series No. 1).

| Gate Release ($ft^3/s$) | Lake Red Bluff Release ($ft^3/s$) | Lake Red Bluff w.s.el. (ft) | t.w.el. (ft) |
|---|---|---|---|
| 1,200 | 4,000 | 252.5 | 238.0 |
| 8,200 | 11,000 | | 239.6 |
| 16,200 | 19,000 | | 241.8 |
| 36,200 | 39,000 | | 245.0 |

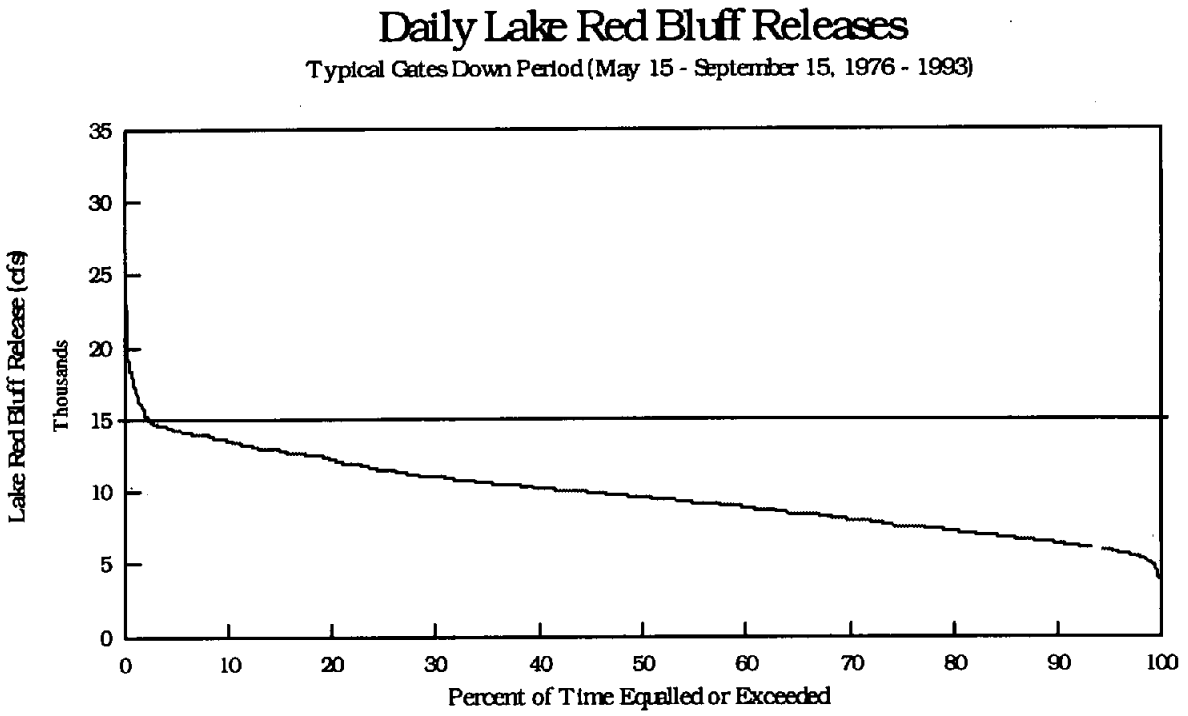


Figure 8. - Percent exceedance presentation of hydrologic data. Design flow at natural breakpoint of 15,000 $ft^3/s$.

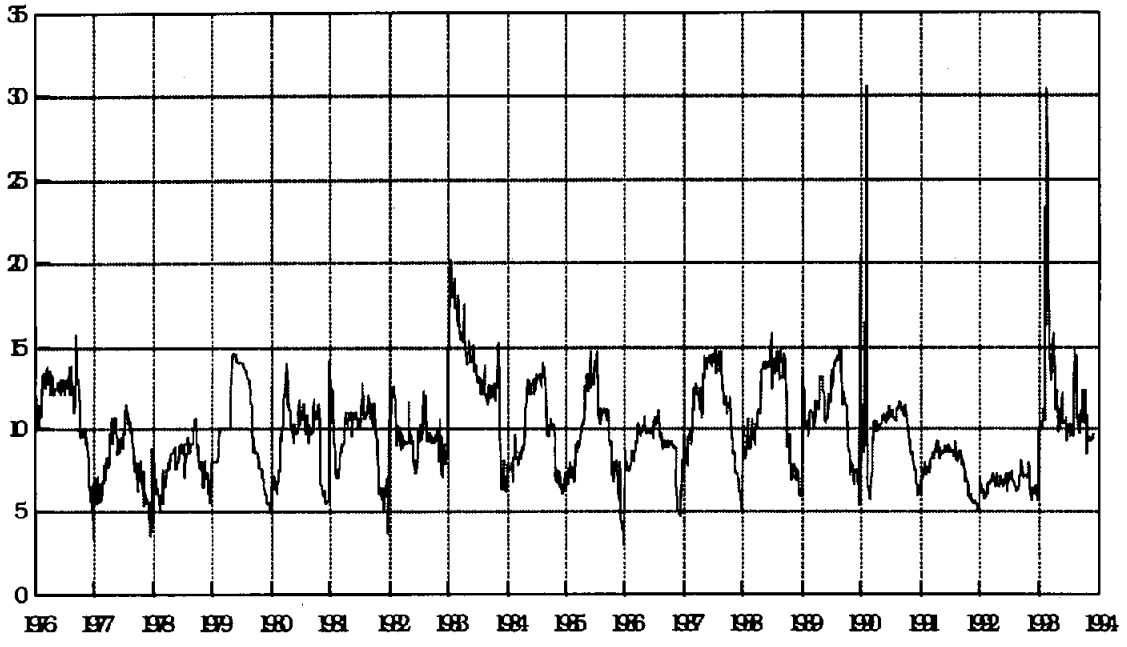


Figure 9. - Daily Lake Red Bluff releases during typical gates down period from 1976 to 1993. Note: 15,000 $ft^3/s$ represents a Lake Red Bluff release which is rarely exceeded (i.e., about 2 percent of the time based on percent accedence curve, fig. 8).

Table 4. - Final investigations - initial testing: gate settings for proposed enlarged ladders operated simultaneously for uniform gate settings (series No. 1).

| Total Release ($ft^3/s$) | Gate Release ($ft^3/s$) | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,200 | 4,000 | 1.0 | - | - | - | - | - | - | - | - | - | - |
| 8,200 | 11,000 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | - | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| 16,200 | 19,000 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | - | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| 36,200 | 39,000 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | - | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |

Following the initial testing, the proposed enlarged ladder configurations were tested simultaneously for those release condition test points selected based upon historic hydrologic data. The test points are given in table 5. Corresponding gate settings have been included in table 6 for each Lake Red Bluff release condition and corresponding RBDD operational configurations. Again, the Lake Red Bluff release column consists of combined spillway and fish ladder releases and represents total Lake Red Bluff releases. Finally, existing ladder configuration were tested for conditions identical to total Lake Red Bluff release hydraulic set points identified in table 5. Table 7 represents gate settings associated with this testing and consists of historically documented field gate settings based on RBDD daily operation logs. All testing for these final investigations has been identified as series Nos. 1 through 4. For each series, various tests are identified which represent tested ladder entrance locations for the respective Lake Red Bluff release conditions and corresponding gate setting configurations. Series No. 1 testing represents uniform gate settings for enlarged ladder concepts operated simultaneously (tables 3 and 4). Series Nos. 2 and 3 testing represents a variety of non-uniform gate setting operations of RBDD for enlarged ladder concepts (tables 5 and 6). Series No. 4 testing represents existing prototype ladder configurations operated for documented RBDD field gate settings (table 7).

Table 5. - Final investigations: proposed enlarged ladders operated simultaneously for non-uniform gate settings (series Nos. 2 and 3).

| Gate Release ($ft^3/s$) | Lake Red Bluff Release ($ft^3/s$) | Lake Red Bluff w.s.el. (ft) | t.w.el. (ft) |
|---|---|---|---|
| 2,200 | 5,000 | 252.5 | 238.3 |
| 7,200 | 10,000 | | 239.8 |
| 12,200 | 15,000 | | 240.9 |
| 17,200 | 20,000 | | 241.8 |

Table 6. - Final investigations: gate settings for proposed enlarged ladders operated in combination for various gate setting configurations (series Nos. 2 and 3).

| Lake Red Bluff Release ($ft^3/s$) | | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Series No.2 - | 5,000 | 0.9 | 1.0 | - | - | - | - | - | - | - | - | - |
| | 10,000 | 1.5 | 0.5 | - | 0.5 | 1.0 | - | 1.0 | 0.5 | - | 0.5 | 1.0 |
| | 15,000 | 1.5 | 1.0 | 0.5 | 1.0 | 1.0 | - | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | 20,000 | 1.5 | 2.0 | 2.0 | 2.0 | 1.0 | - | 1.0 | 1.5 | 2.0 | 1.5 | 1.0 |
| Series No. 3 - | 10,000 | 1.5 | 0.5 | - | 0.5 | 1.0 | - | 1.0 | 0.5 | - | 0.5 | 1.0 |
| Configuration No. 1 - | 15,000 | 1.5 | 0.5 | - | - | 0.5 | - | 1.0 | 1.5 | 2.0 | 1.5 | 1.0 |
| Configuration No. 2 - | 15,000 | 1.5 | 2.0 | 2.0 | 1.5 | 1.0 | - | 1.0 | 0.5 | - | 0.5 | 1.0 |
| Configuration No. 3 - | 15,000 | 1.5 | 1.0 | 0.5 | 1.0 | 1.0 | - | 1.0 | 1.0 | 1.5 | 1.5 | 1.0 |
| Configuration No. 1 - | 20,000 | 1.5 | 2.0 | 2.0 | 2.0 | 1.0 | - | 1.0 | 1.5 | 2.0 | 1.5 | 1.0 |
| Configuration No. 2 - | 20,000 | 1.5 | 1.5 | 1.5 | 1.0 | 1.0 | - | 1.0 | 2.0 | 3.0 | 2.0 | 1.0 |

Table 7. - Final testing: existing prototype ladder configurations operated in combination for typical field gate setting conditions. Hydraulic set points are consistent with those of table 5 (series No. 4).

| Gate Release ($ft^3/s$) | Total Release ($ft^3/s$) | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4,260 | 5,000 | 1.5 | - | - | - | 0.5 | - | 0.5 | - | - | - | 1.0 |
| 9,260 | 10,000 | 1.5 | 1.0 | 0.5 | - | - | - | 1.0 | - | 2.0 | 1.0 | 1.0 |
| 14,260 | 15,000 | 1.5 | 1.0 | 1.0 | - | - | - | 1.0 | 1.0 | 1.0 | 2.0 | 2.4 |
| 19,260 | 20,000 | 1.5 | 2.0 | 2.5 | 1.5 | 1.0 | - | 1.0 | 1.5 | 2.5 | 1.5 | 1.0 |

Testing for Lake Red Bluff release conditions higher than 20,000 $ft^3/s$ was not selected because these conditions have occurred less than 2 percent of the time for the historic period of record. Thus, demonstration of enlarged ladder attraction flow performance for release conditions higher than 20,000 $ft^3/s$ was not warranted because ladder performance above this point would provide limited additional benefit.

### Model Operation

Water was supplied to the physical model via the laboratory 100-hp variable speed motor-driven pump and venturi measurement system. A rock baffle was constructed at the head of the model to distribute and settle flows entering the model. The water surface elevation (w.s.el.) for Lake Red Bluff was measured using a point gage with a vernier graduated to 0.001 ft. Tailrace water surface elevation was measured in the same manner. Gate settings were adjusted using a lead screw adjustment mechanism. Gate settings were measured by determining the adjustment mechanism number of revolutions and applying the thread lead. Flows were supplied to each ladder independently using three 1.5-hp pumps. Flow rates for each ladder were measured using acoustic, external mount flowmeters located on each ladder influent line.

## RESULTS

The results of this study for each test condition have been presented as color contour plots of the velocity vector field data. Such a presentation provides a visual indication of tailrace velocity field patterns. However, the data presentation does not give an accurate indication of velocities along the stilling basin located immediately downstream from the diversion dam. This condition is the result of limitations in acquiring physical model data along the diversion dam stilling basin, because of the data acquisition techniques used. In fact, velocities along the stilling basin are expected to be greater than those measured just downstream, a feature which the data presentation plots do not show. The primary results of both preliminary and final investigations are given as follows.

### Preliminary Investigations

The results of preliminary testing, which was completed in 1995, demonstrate general attraction flow features of the proposed enlarged ladders for uniform gate settings. Those results have been documented by Kubitschek (1995) and are briefly summarized as follows:

***800-ft$^3$/s Right Abutment Ladder Results.*** - The three ladder entrance locations tested indicate some influence of ladder entrance location on near and far field attraction flow features. The two upstream most ladder entrances are oriented perpendicular to the diversion dam tailrace and tend to produce favorable lateral release penetration. This penetration is particularly evident for low end Lake Red Bluff Release conditions (i.e., 5,000 to 10,000 ft$^3$/s). The downstream most ladder entrance represents a 45-degree downstream orientation with respect to the diversion dam tailrace and produces better far field attraction flow features for low end Lake Red Bluff release conditions compared with the upstream ladder entrances. This result is attributable, in part, to the entrance orientation, which tends to produce improved far field attraction at the expense of less favorable near field lateral penetration. As Lake Red Bluff releases are increased, ladder releases become masked by higher spillway releases, which tend to dominate the tailrace velocity field.

***1,000-ft$^3$/s Center Ladder Results.*** - The three entrance locations on either side of the center ladder exhibit results similar to the 800-ft$^3$/s right abutment ladder in regard to entrance location and orientation. The two upstream most ladder entrances located on each side of the structure, and oriented perpendicular to the diversion dam tailrace, were observed to provide improved lateral penetration over the downstream most 45-degree ladder entrances. However,

the downstream most entrances tend to produce improved far field attraction flow features, but at the expense of reduced lateral near field penetration. Furthermore, as Lake Red Bluff releases were increased, attraction flow performance diminished as spillway releases consisting of a higher percentage of total Lake Red Bluff releases began to mask ladder releases, making high velocity zones no longer distinguishable.

***1,000-ft³/s Left Abutment Ladder Results.*** - Again, results obtained for the left abutment 1,000-ft³/s ladder were similar to those obtained for the right abutment and center ladders. The two upstream ladder entrances oriented perpendicular to the diversion dam tailrace provided the best lateral penetration but not necessarily the best far field attraction flow features. Improved far field attraction flow features were observed with the use of the downstream most 45-degree oriented ladder entrance. In addition, the results exhibited improved overall far field attraction flow performance over those of the right and center ladder results. This result was observed as the existence of distinct high velocity zones extending directly from the ladder entrances well downstream into the tailrace channel for higher Lake Red Bluff release conditions compared with the right and center ladder results. The fact that this ladder provides improved far field attraction flow features is attributed to the full 1,000 ft³/s being passed through a single ladder entrance. This flow is in contrast to the center ladder, which virtually represents two 500-ft³/s ladders because of the flow split. However, even for the left abutment ladder, spillway releases were found to mask ladder releases for high end flow conditions (i.e., Lake Red Bluff releases of 19,000 to 39,000? ft³/s).

***3,000-ft³/s Left Abutment Ladder Results.*** - The 3,000-ft³/s left abutment ladder configuration was observed to offer the best far field attraction flow features over the full range of Lake Red Bluff release conditions tested. All three ladder entrances were operated simultaneously to accommodate the increased discharge and meet entrance velocity criteria. Because of the size (i.e., discharge) of this ladder, strong far field attraction flow features were observed. However, this size in and of itself is not likely practical.

Although ladder entrance location influences attraction flow performance, selection of such strongly depends on gate operation adjacent to ladder entrances and corresponding fish staging locations. In this respect, ladder entrance orientation will fall under the same criteria. In any case, these results represent an indication of individual ladder performance and thus provide a baseline for comparison with enlarged ladder performance for various RBDD spillway gate operating scenarios. The results of the 1,000-ft³/s left abutment ladder testing indicate this size to be favorable for the range of Lake Red Bluff release conditions tested given the historic hydrologic data. In addition, these results indicate that the center ladder configuration may be less than optimal because the flow split associated with this concept virtually creates two 500-ft³/s ladders. This condition may not be desirable from a far field attraction flow standpoint, although such a center ladder configuration produces strong lateral coverage, which is desirable. Finally, the 3,000-ft³/s left abutment ladder size, although large enough to perform well for Lake Red Bluff release conditions above 20,000 ft³/s, is not likely to be practical. The high cost associated with this size of ladder, combined with the limited additional benefit given the results of the historic hydrologic data analysis, make this option impractical. The results of the 1,000-ft³/s left abutment ladder testing provide the strongest indication that this ladder size is likely appropriate for RBDD given historic hydrologic conditions.

All data results for these preliminary investigations have been included as appendix A. A brief interpretation and discussion of the results for each test is also provided.

**Final Investigations**

The results of final testing, in general, show that favorable attraction flow characteristics are achievable with the use of enlarged ladders. In addition, these results demonstrate the most effective gate operating configurations which produce favorable attraction flow features for the range of Lake Red Bluff release conditions tested.

***Total Lake Red Bluff Release of 4,000 to 5,000 $ft^3/s$.***-For low end Lake Red Bluff release conditions, both existing and enlarged ladder configurations produce strong near and far field attraction flow features that extend directly from ladder entrances well downstream into the RBDD tailrace reach. Figures 10 and 11 represent the results of physical model testing for both the existing and proposed enlarged ladder configurations, respectively, for a total Lake Red Bluff release of 5,000 $ft^3/s$. In both cases, strong near and far field attraction flow features are illustrated by distinct high velocity zones. Comparison of these results (figs. 10 and 11) indicates that the enlarged ladder configurations produce more prominent high velocity zones that extend directly from ladder entrances. This result is attributed to the fact that the enlarged ladder releases consist of a greater percentage of the total Lake Red Bluff release than the existing ladders. For both cases, spillway releases were made through adjacent gates as required to establish fish staging locations consistent with ladder entrance locations.

***Total Lake Red Bluff Release of 10,000 to 11,000 $ft^3/s$.***-Figures 12 and 13 represent existing ladder and enlarged ladder results for mid-range release conditions, respectively. In both cases, favorable far field attraction flow features exist. However, the enlarged ladders exhibit better near field attraction flow zones of influence. Downstream oriented center ladder entrances were also tested for this release condition. Figure 14 represents these results. Figure 15 represents the results of uniform gate settings for the proposed enlarged ladders for total Lake Red Bluff release conditions of 10,000 $ft^3/s$. For this RBDD operating configuration, no distinct far field attraction flow zones exist. Thus, efficient attraction and guidance to ladder entrances will be difficult to achieve when spillway releases are uniformly distributed across RBDD.

***Total Lake Red Bluff Release of 15,000 $ft^3/s$.***-Comparison of existing ladder (fig. 17) and enlarged ladder (fig. 16) results for this test condition indicates that improved near field attraction flow features exist for the enlarged ladders. However, these results again illustrate the fact that distributing spillway releases across the diversion dam may not be optimal. Figures 18 and 19 represent two examples of improved far field attraction flow features. These results were achieved by crowning one side of the diversion dam while maintaining some spillway releases through those gates adjacent to ladder entrances for the other side. Although the imbalanced crowning flow approach is unconventional, the results of this study show that favorable attraction flow features may be achieved. Thus, such an operational approach is worth consideration.

***Total Lake Red Bluff Release of 19,000 to 20,000 $ft^3/s$.***-For these conditions, spillway releases become more dominant over the tailrace velocity field. In this case, enlarged ladder releases comprise a small percentage of the total Lake Red Bluff release and exert little influence on tailrace velocity field patterns. A fully crowned flow approach is required to pass these high end Lake Red Bluff releases while meeting RBDD operating criteria and sustaining adequate guidance and attraction flow features. Figure 20 provides a good example of the potential for the proposed enlarged ladders to achieve these requirements. Comparison of existing ladder performance (fig. 21) with enlarged ladder performance (fig. 20) illustrates

similar far field attraction flow features, a result of similar spillway release magnitudes. However, the enlarged ladder configurations exhibit stronger near field zones of influence compared with existing ladders, which is critical for efficient passage under these conditions.

***Total Lake Red Bluff Release of 39,000 $ft^3/s$.***-For these conditions, spillway releases overwhelm ladder releases and dominate the tailrace velocity field. Higher gate settings required to pass these Lake Red Bluff releases fully mask ladder releases and have the potential to create a barrier to passage. Figure 22 represents enlarged ladder test results for the intermediate ladder entrance locations for these Lake Red Bluff release conditions. Again, because enlarged ladder releases comprise a small percentage of the total Lake Red Bluff release, the influence is limited to the near field. As such, crowning flow operation of RBDD is required to generate far field attraction and guidance.

All data results for these final investigations have been included as appendix B. A brief interpretation and discussion of the results for each test is also provided.

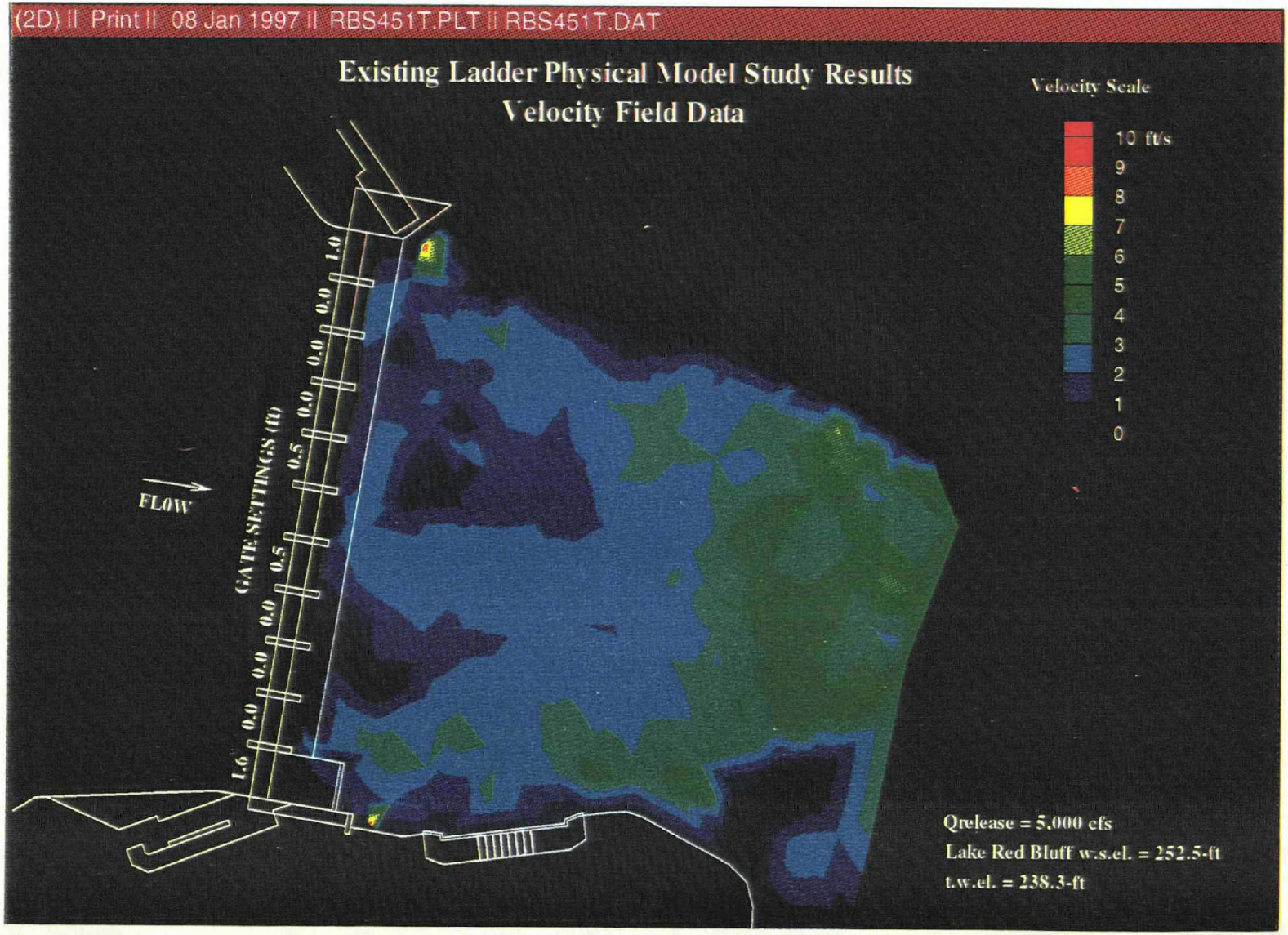


Figure 10. - Existing ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 5,000 $ft^3/s$.

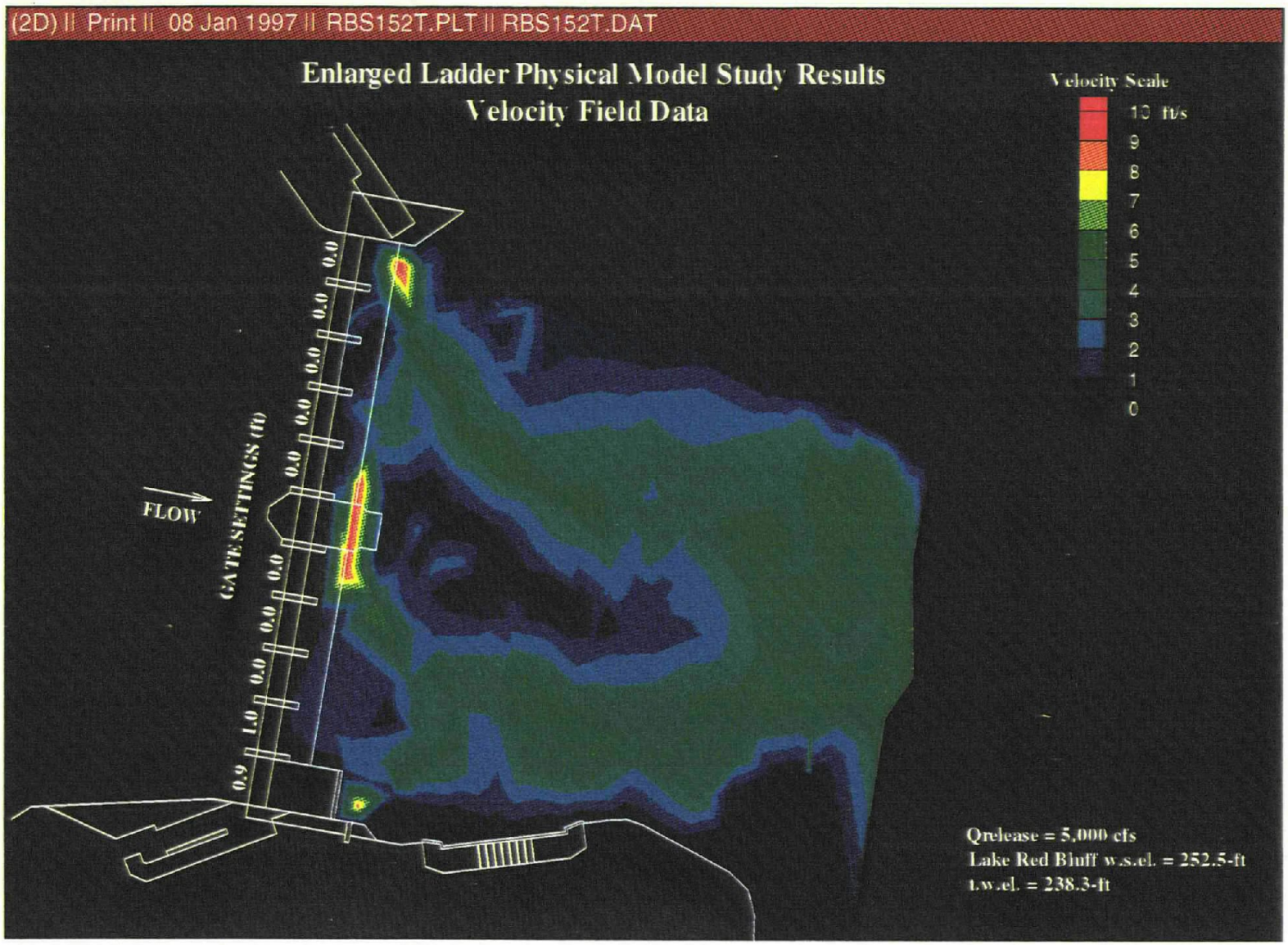


Figure 11. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 5,000 $ft^3/s$.

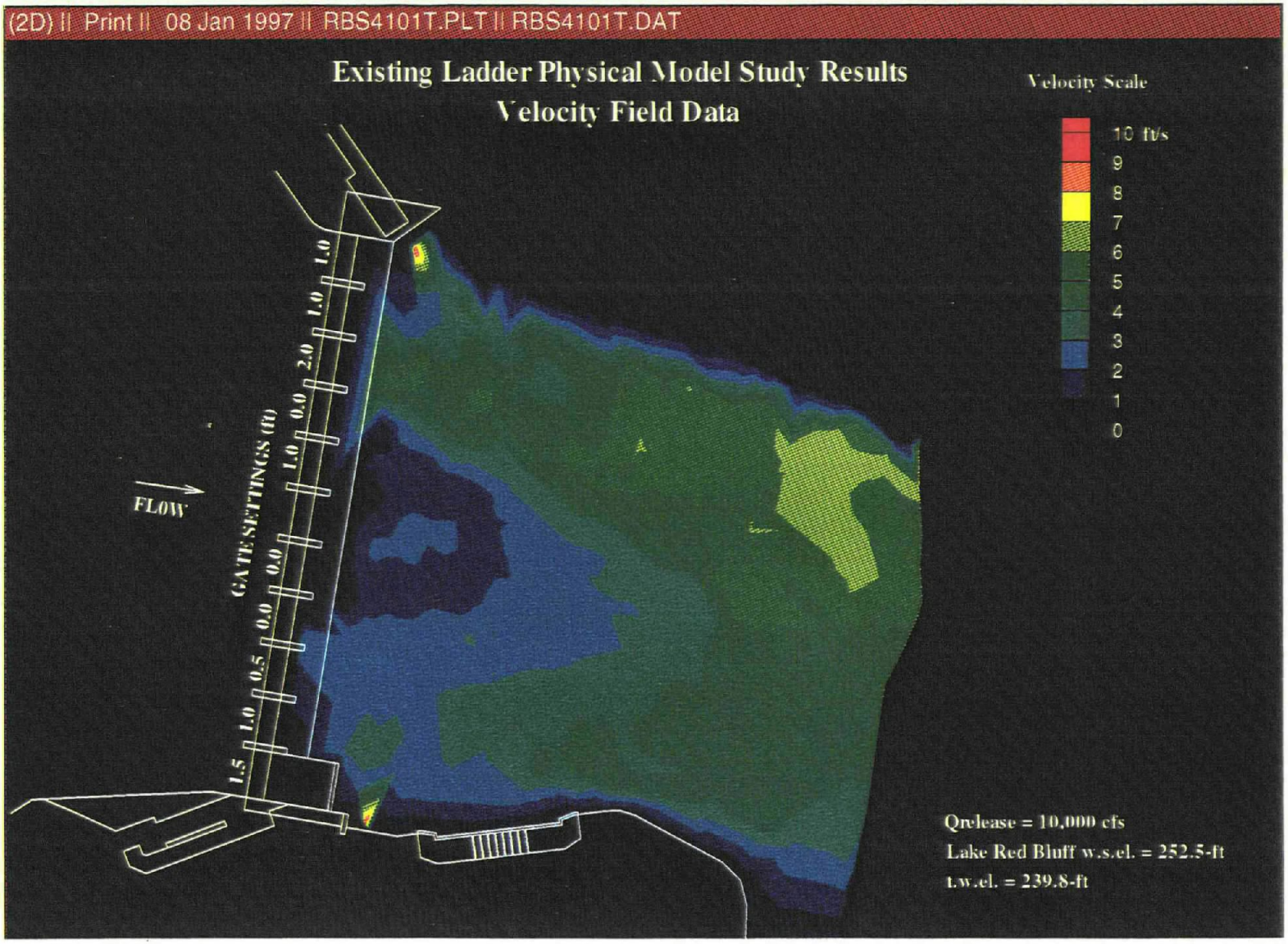


Figure 12. - Existing ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 10,000 $ft^3/s$.

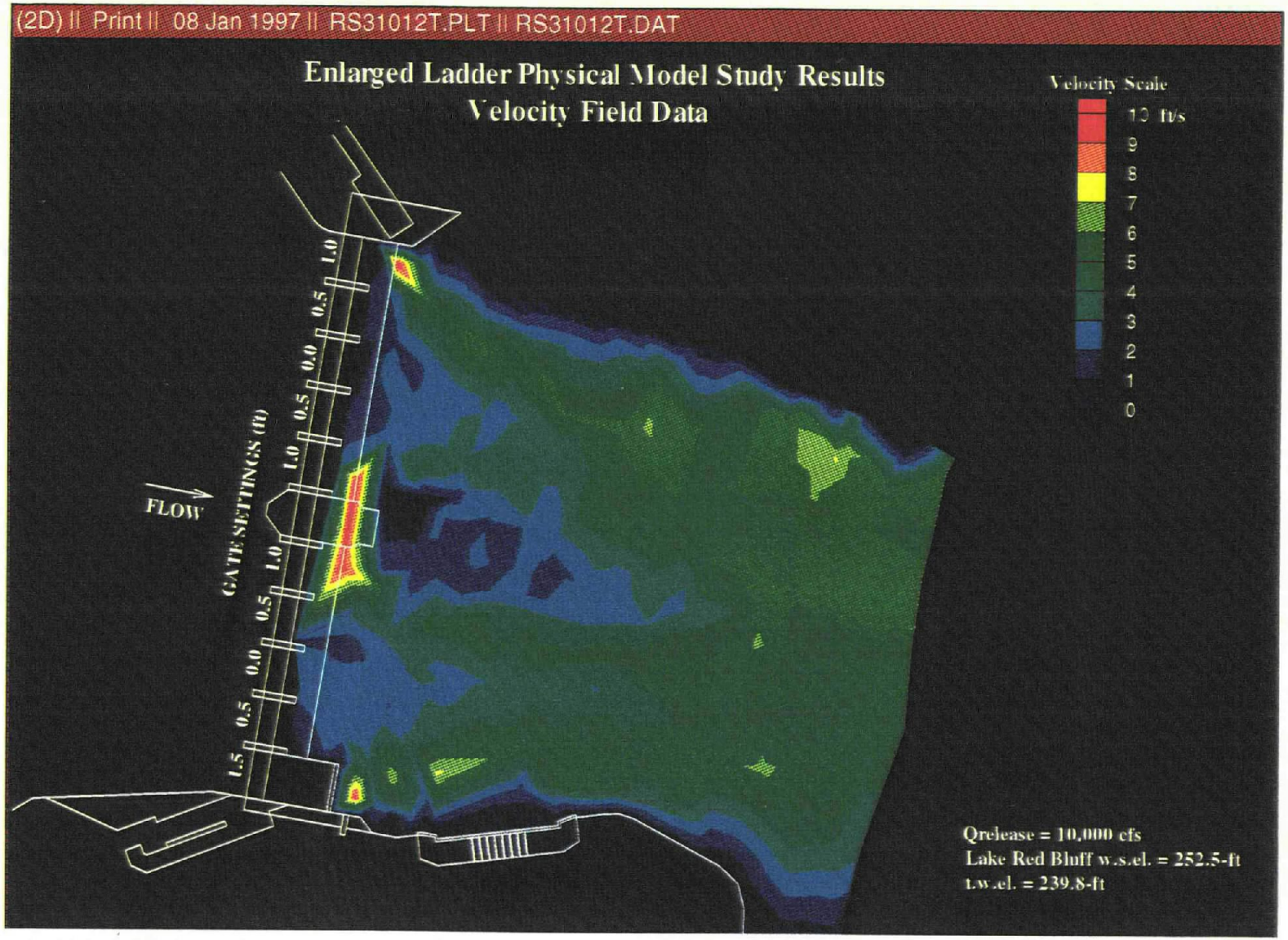


Figure 13. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 10,000 $ft^3/s$.

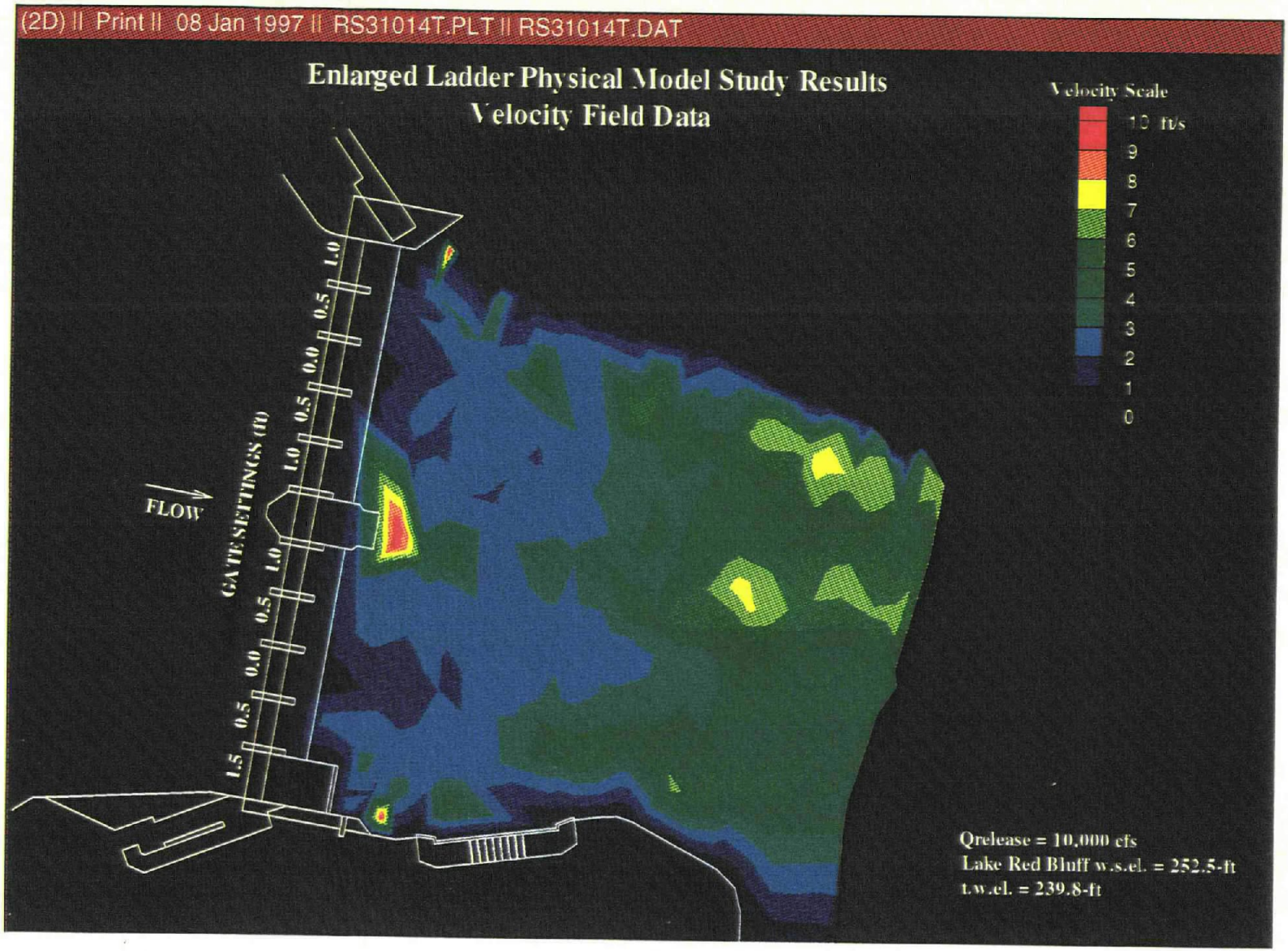


Figure 14. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 10,000 $ft^3/s$. Note downstream oriented center ladder entrances.

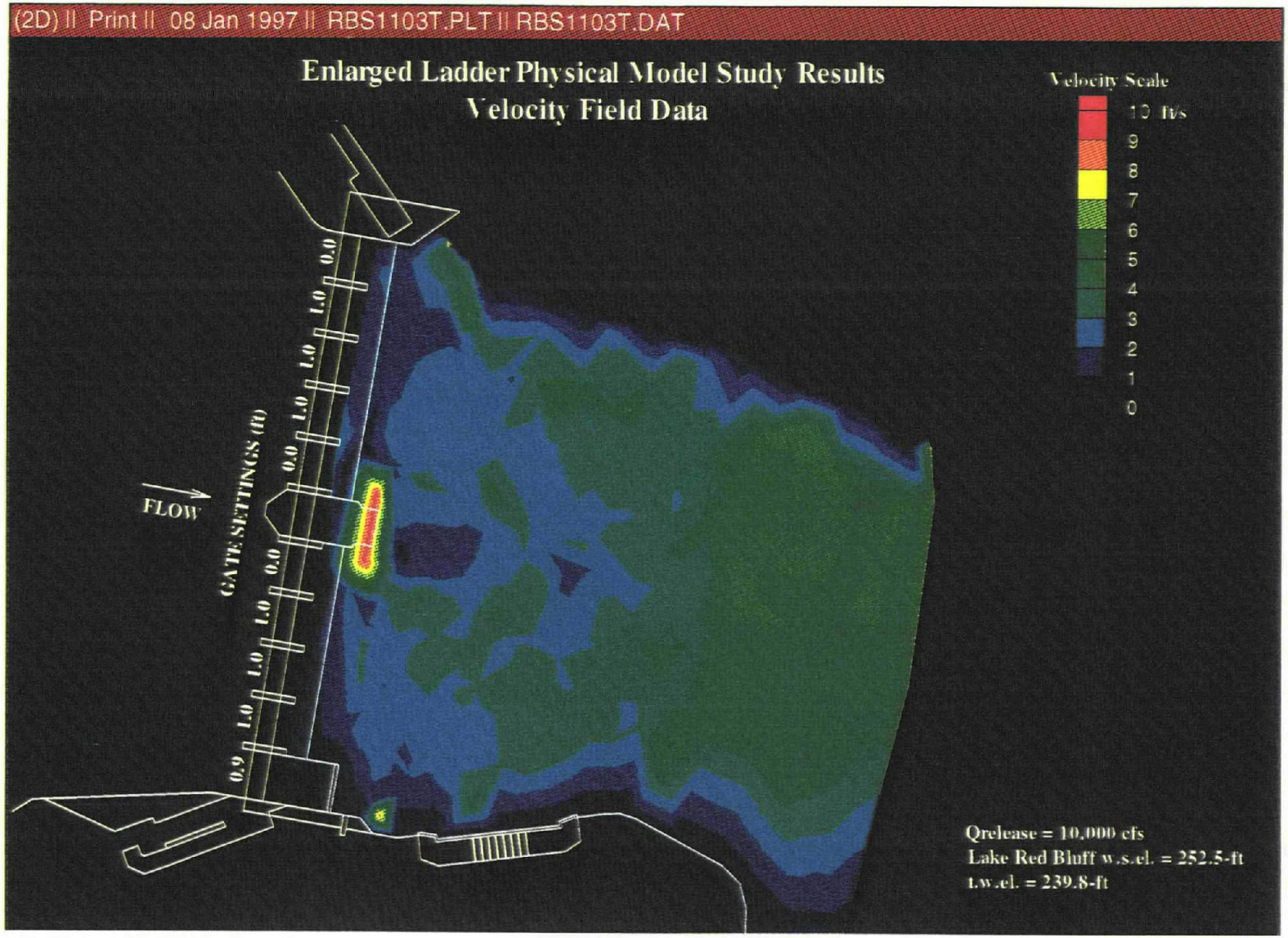


Figure 15. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 10,000 $ft^3/s$. Note: spillway releases distributed across diversion dam.

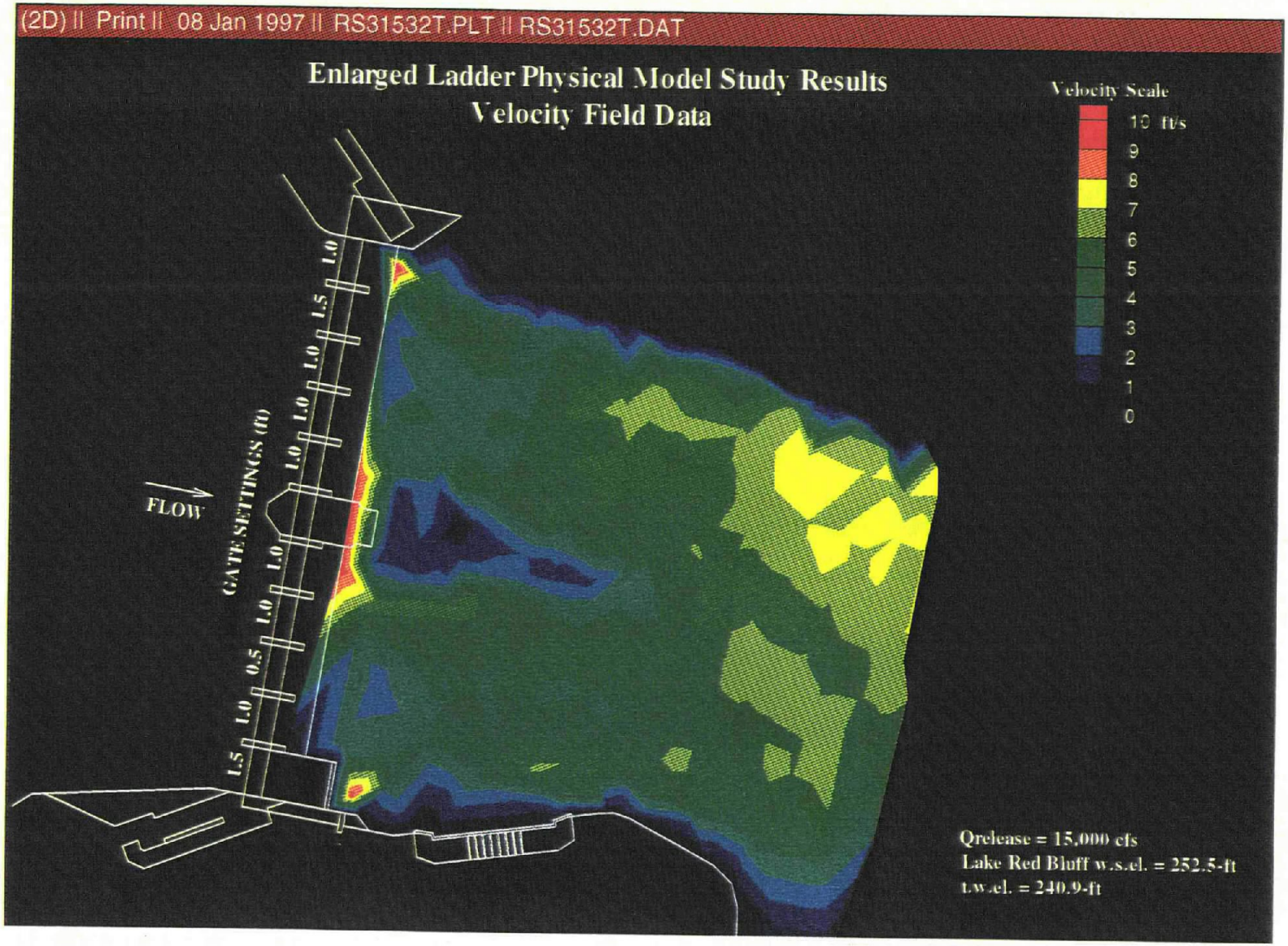


Figure 16. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 15,000 $ft^3/s$.

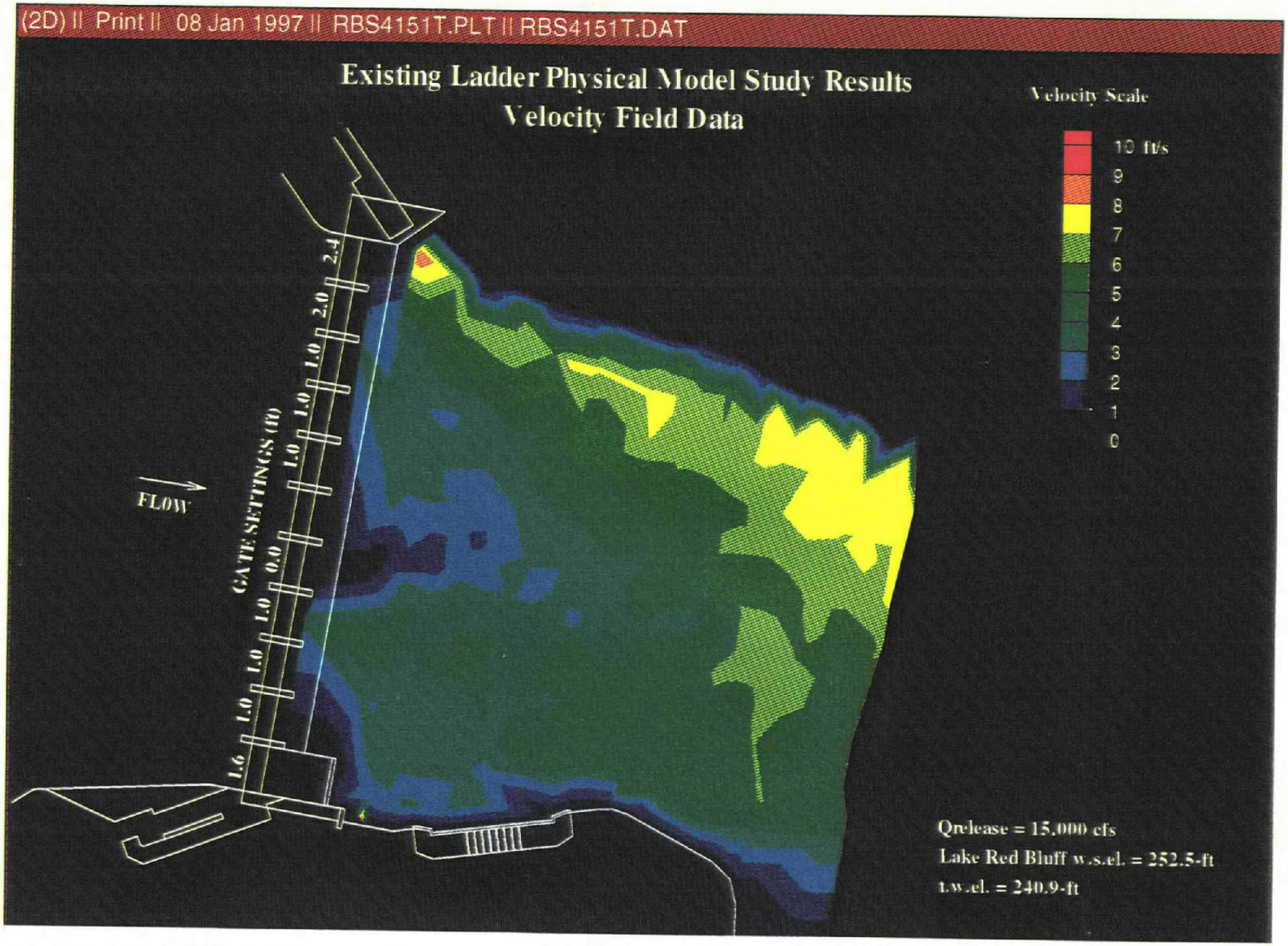


Figure 17. - Existing ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 15,000 $ft^3/s$.

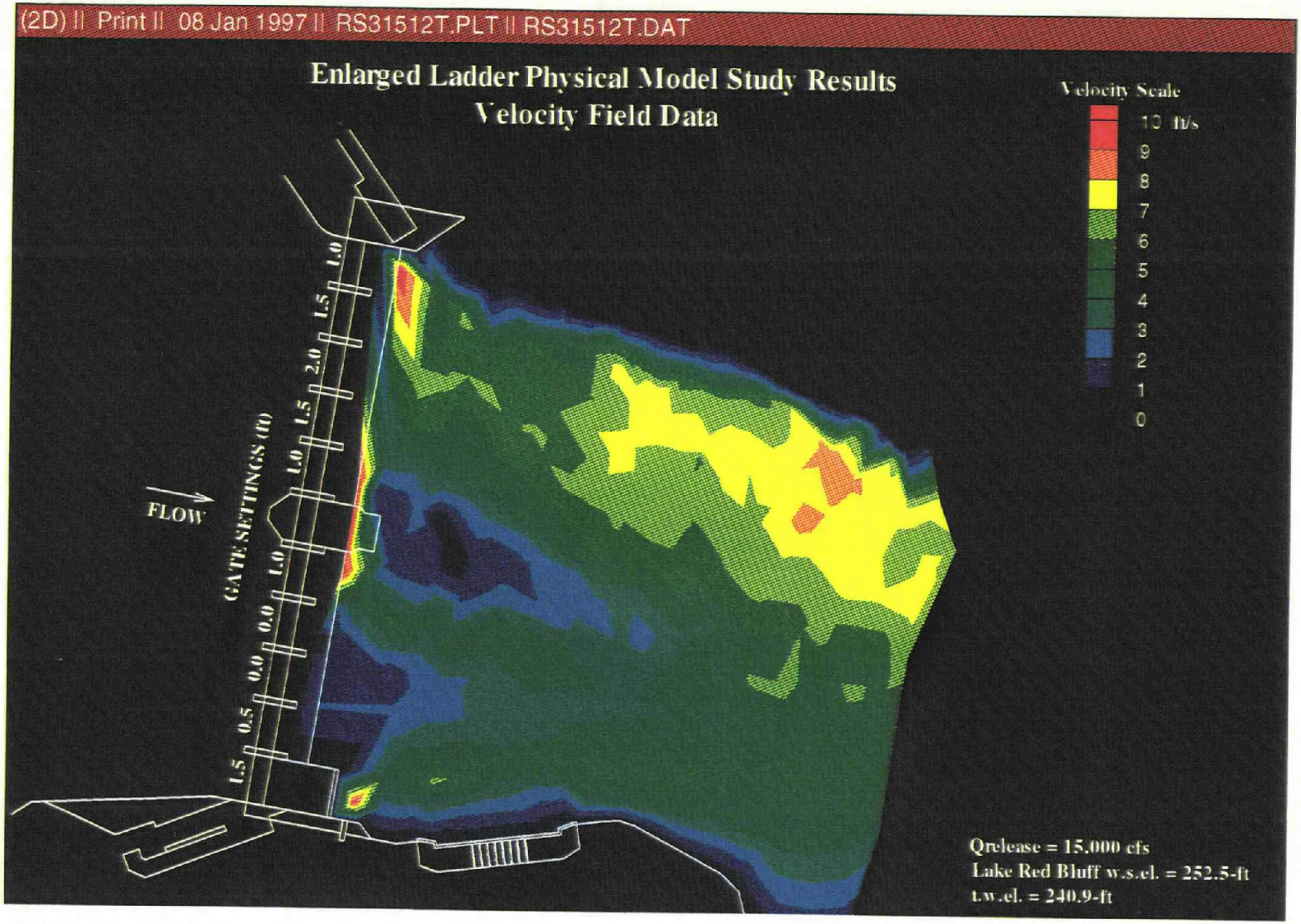


Figure 18. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 15,000 $ft^3/s$. Note: imbalanced spillway release distribution produces strong far field attraction flow features.

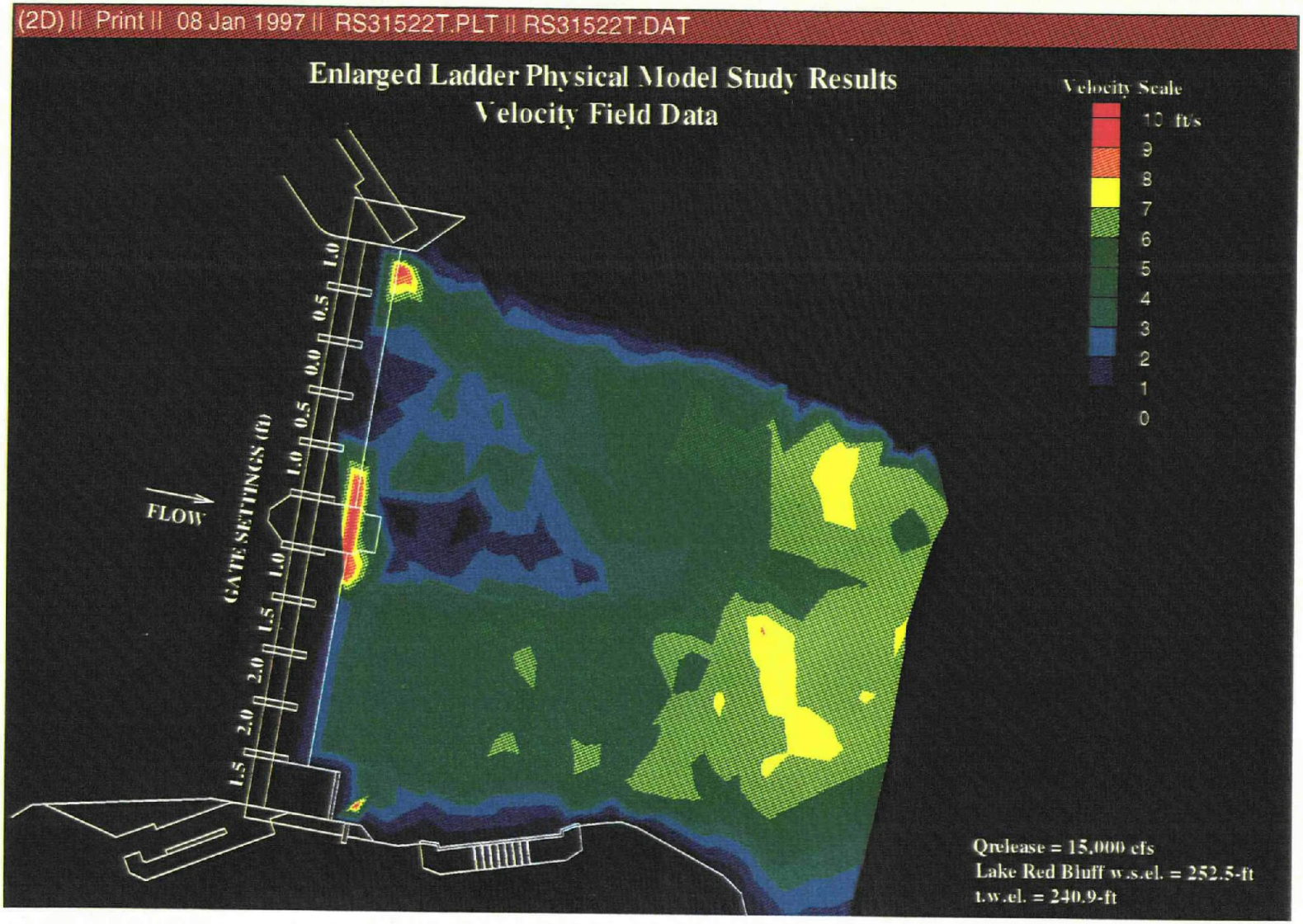


Figure 19. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 15,000 $ft^3/s$. Note: again, imbalanced spillway release distribution produces strong far field attraction flow features.

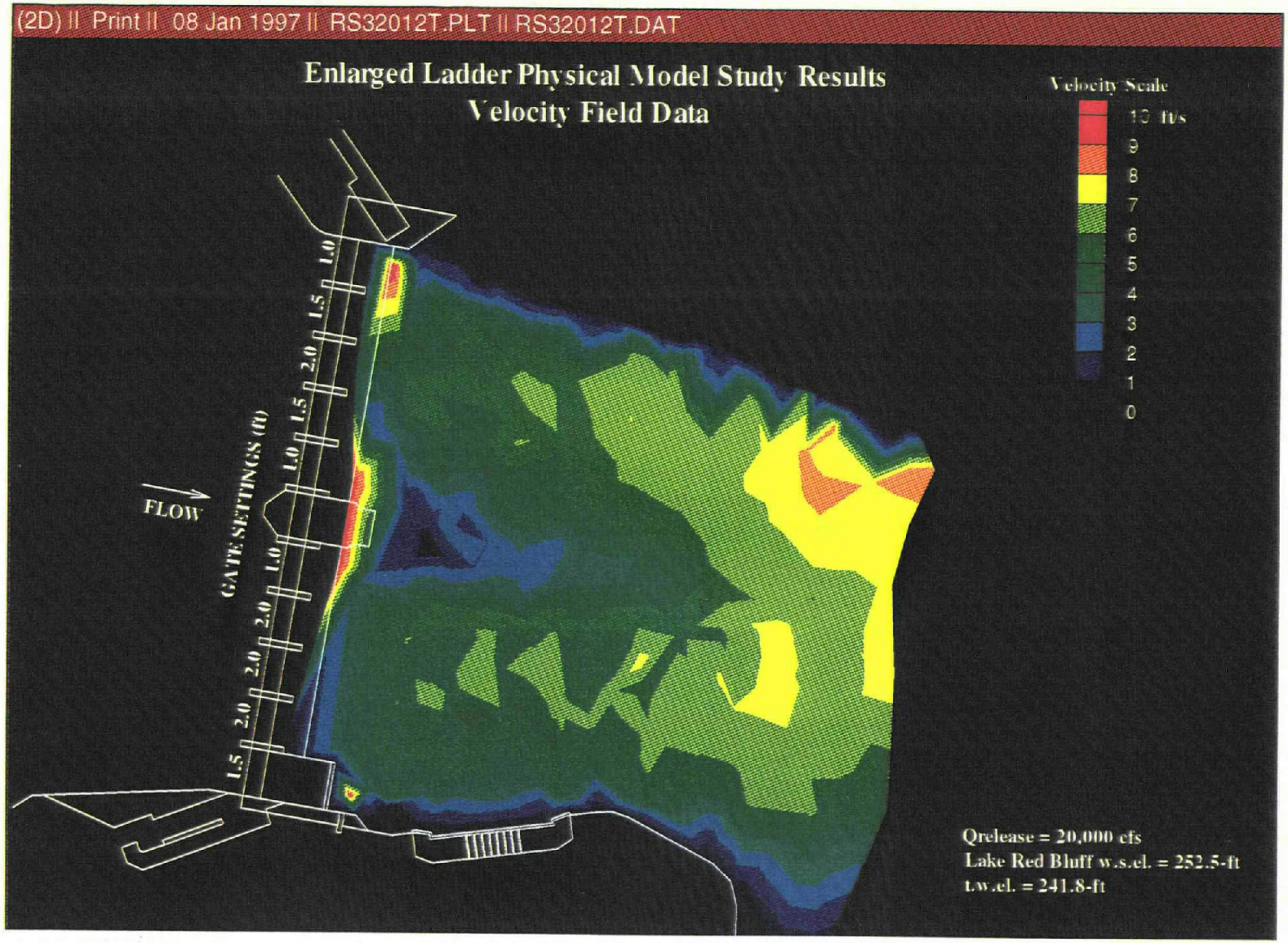


Figure 20. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 20,000 $ft^3/s$.

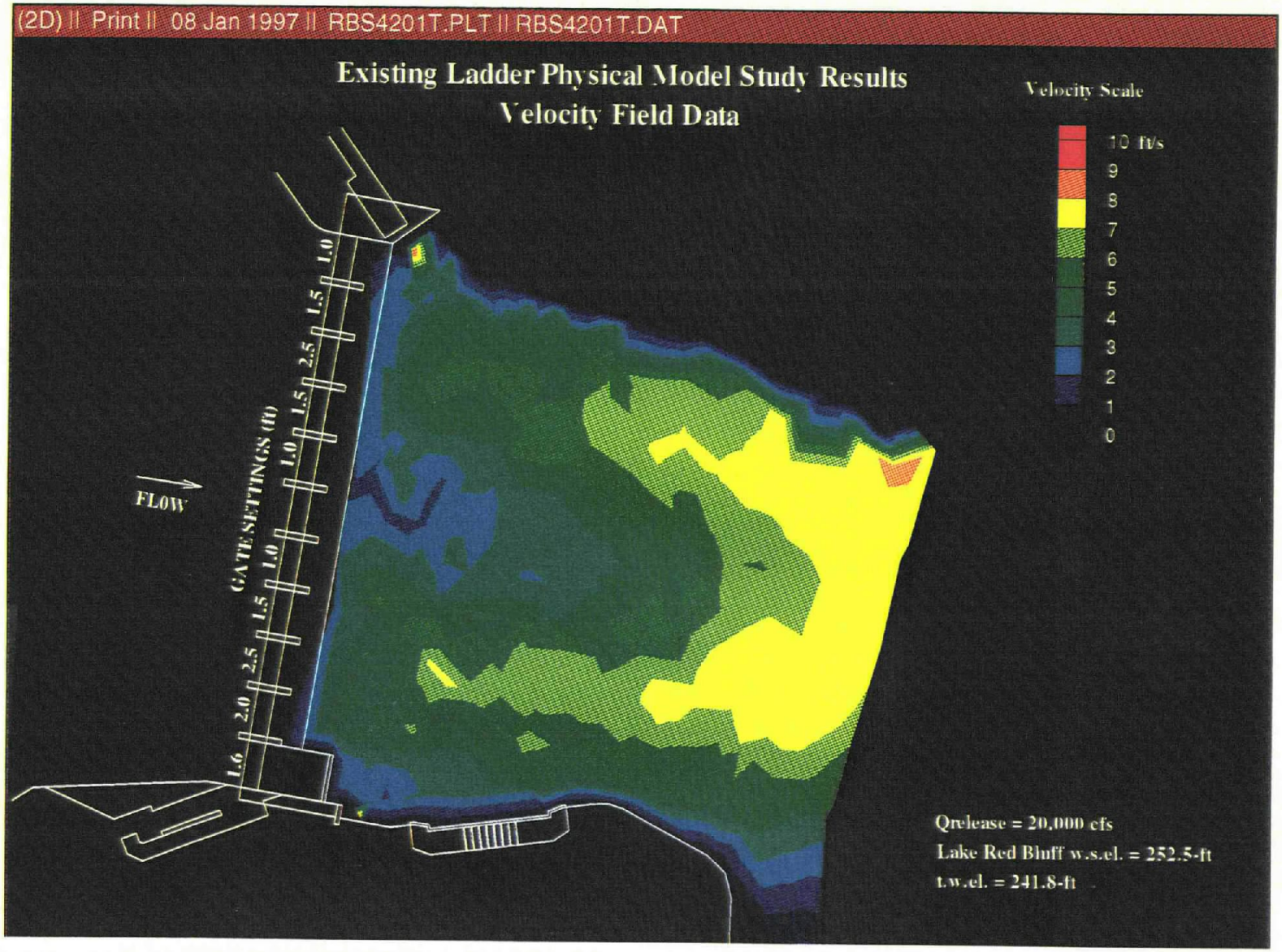


Figure 21. - Existing ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 20,000 $ft^3/s$.

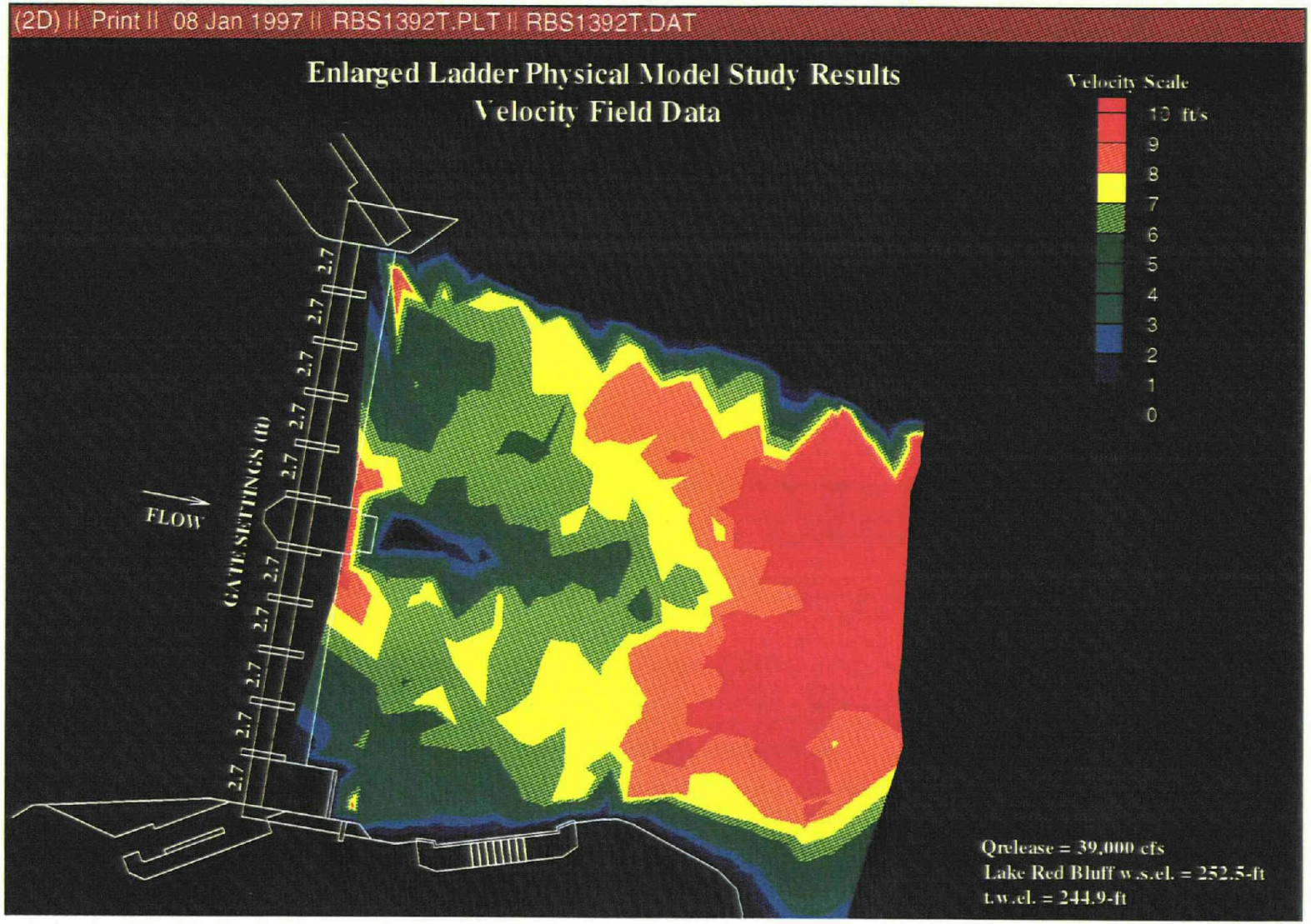


Figure 22. - Proposed enlarged ladder test results. Contour plot of velocity field data for RBDD tailrace for Lake Red Bluff release conditions of 39,000 $ft^3/s$. Note: spillway releases fully mask ladder releases and produce poor far field attraction flow features.

## RESULTS SUMMARY AND DISCUSSION

The results of this study provide insight into required ladder sizes and operating configurations which have the greatest potential for improving adult fish passage at RBDD. Four operating parameters which influence attraction flow conditions have been identified and include:

- RBDD spillway gate operations
- Fish ladder size (discharge)
- Fish ladder entrance location
- Fish ladder entrance orientation

### RBDD Spillway Gate Operation

Effective attraction flow conditions consist of high velocity zones which extend directly from ladder entrances well downstream in the tailrace reach of the diversion dam. Such attraction flow conditions provide the opportunity for fish to sense and locate ladder entrances. Favorable near field attraction consists of strong lateral coverage out in front of the spillway, and favorable far field attraction consists of distinct high velocity zones well downstream from the diversion dam. In consideration of these objective attraction flow features and based on the results of this study, it is apparent that the manner in which RBDD is operated has a significant impact on attraction flow conditions throughout the tailrace.

For low range Lake Red Bluff release conditions (i.e., 5,000 to 10,000 $ft^3/s$), ladder releases comprise a large percentage of the total release. As such, ladder releases dominate the tailrace velocity field and produce strong near and far field attraction flow features. In this case, RBDD should be operated such that fish staging locations, generated by spillway releases, are consistent with ladder entrances. This consistency requires spillway releases to be made through gates adjacent to ladder entrances. A secondary benefit of this approach is in providing additional attraction flow.

For mid-range Lake Red Bluff releases (i.e., 10,000 to 15,000 $ft^3/s$), spillway releases become significant because a reduced percentage of the total Lake Red Bluff release is passed through ladders. However, various RBDD operational schemes can be identified, using the results of this study, which produce favorable attraction flow conditions. In this case, adjacent gate releases or crowning flow releases or a combination of the two may be used as necessary to both position fish staging locations near ladder entrances and provide far field attraction to those ladder entrances. The crowning flow approach consists of successively higher spillway releases passed through gates which are located successively farther away from ladder entrances.

For high range Lake Red Bluff releases (i.e., 15,000 to 20,000 $ft^3/s$ and above), the tailrace velocity field is predominantly generated by spillway releases because ladder releases comprise a small percentage of the total release. For these conditions, up migrating fish will likely be attracted to spillway releases. It is perceived that as fish move upstream, staging will occur just downstream from highly turbulent air entrainment zones because passage is not available through spillway gates. At this point, fish will begin to search for a passage. The crowning flow approach takes advantage of this behavior by guiding fish toward ladder entrances where the near field attraction flow features of the ladders provide the opportunity for fish to sense and locate ladder entrances. The results of this study indicate that favorable far field attraction flow features can be generated using a fully crowned flow approach to RBDD spillway gate

operations. However, it is important for this range of Lake Red Bluff releases that strong near field attraction flow features exist to achieve efficient passage by minimizing delay. In addition, these results provide a strong argument against uniformly distributing spillway releases across the diversion dam. Operation in such a manner tends to mask ladder releases for lower spillway release conditions compared with the crowning flow approach.

For any spillway gate operating configuration, dead end or false attraction flow conditions should be avoided. Additional field studies should be conducted to increase the level of certainty regarding fish staging locations with respect to RBDD spillway gate operations. In addition, any final enlarged ladder design should contain the appropriate degree of flexibility such that passage performance with respect to spillway gate operation can be investigated and refined.

**Fish Ladder Size (Discharge)**

The primary objective of this study involved determining the potential for improved adult fish passage at RBDD through the use of enlarged fish ladders. Thus, it was important to determine ladder size, in terms of discharge, required to generate sufficient attraction flow features. The results of this study indicate that the selected enlarged ladder sizes are capable of providing favorable attraction flow features for the range of Lake Red Bluff release conditions identified based on historic hydrologic data. However, it should be noted that the Sacramento River at RBDD is regulated. Although historic Lake Red Bluff release conditions reflect current operating procedures for Shasta Dam located upstream, historic conditions are not guaranteed to exist in the future. Future decisions regarding how Shasta Dam is operated may influence conditions at RBDD. This factor is an important consideration in the interpretation of these results and the implementation of any solution for improving fish passage at RBDD.

**Fish Ladder Entrance Location**

The location of fish ladder entrances was found to have some influence on near and far field attraction flow performance. However, the primary purpose of having multiple entrances is to provide a level of flexibility in positioning ladder entrances near fish staging locations. For the full range of Lake Red Bluff release conditions tested and the various RBDD spillway gate operating scenarios, a range of fish staging locations exists with respect to gate settings which are adjacent to ladder entrances. Higher adjacent gate settings push fish staging locations farther downstream from the diversion dam. Thus, the need for flexibility in ladder entrance location is required.

**Fish Ladder Entrance Orientations**

As with fish ladder entrance location, orientation has some influence on near and far field attraction flow features. In particular, orientation becomes important in generating lateral penetration. The results of this study indicate that the best lateral penetration is achieved using ladder entrance orientations which are perpendicular to the diversion dam tailrace. For low end Lake Red Bluff release conditions a trade off exists between lateral penetration and far field attraction. Although ladder entrances oriented perpendicular to the diversion dam tailrace produce strong lateral coverage, far field attraction flow features were reduced. This case is in contrast to the results obtained for the 45-degree downstream oriented ladder entrances, which produced strong far field attraction flow features at the expense of reduced

lateral coverage. For mid-range and high end Lake Red Bluff releases, ladder entrance orientation becomes less important because spillway releases dominate far field tailrace velocity conditions. In this case, the 45-degree downstream oriented ladder entrances appear to have the most merit by optimizing the balance between lateral penetration and the far field attraction zone of influence. Again, some flexibility in the final design with respect to ladder entrance orientation is recommended should field refinement be required.

## RECOMMENDATIONS

- Based upon the results of this study, the enlarged ladder alternative has significant potential for improving adult fish passage at RBDD and is recommended for further development and implementation.

- The appropriate ladder entrance locations and orientations should be selected consistent with likely fish staging locations as a function of adjacent gate settings. Thus, sufficient flexibility for field investigation and refinement of performance is recommended for the final design.

- Based on the results of this study for enlarged ladder configurations, it is recommended that spillway releases for low end Lake Red Bluff release conditions (i.e., 5,000 to 10,000 $ft^3/s$) be made through gates adjacent to ladder entrances in order to position fish staging locations near ladder entrances and to supplement far field attraction flow features. For mid-range Lake Red Bluff releases (i.e., 10,000 to 15,000 $ft^3/s$), spillway releases may be made through adjacent gates or by using the crowning flow approach. This range represents the transitional range between the adjacent gate and crowning flow operational strategies. In either case, false or dead end attractions should be avoided. For high end Lake Red Bluff release conditions (i.e., 15,000 to 20,000 $ft^3$ and above), the fully crowned approach is recommended to pass river flows while maintaining strong far field attraction flow and guidance features. To achieve this condition, gate settings should be tapered with successively higher spillway releases through gates which are located successively farther from ladder entrances. In this manner, the tapering hydraulic barrier may be used to take advantage of behavior and guide fish toward ladder entrances.

- Finally, additional field studies are recommended prior to final design and implementation of enlarged ladders. Such studies would include radio tagging investigations to improve the level of certainty regarding fish staging locations with respect to RBDD spillway gate operating configurations. The results would be used to identify the range of ladder entrance locations required to accommodate the likely range of fish staging locations.

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## Mission

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