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PRICE-STUBB DIVERSION DAM FISH PASSAGE STRUCTURE, COLORADO RIVER

1:20 SCALE PHYSICAL MODEL STUDY

April 2001

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13. ABSTRACT ***(Maximum 200 words)***

A 1:20 Froude-scale physical model study of three proposed fish-passage structures for Price-Stubb Diversion Dam was conducted at the Bureau of Reclamation's Water Resources Research Laboratory in Denver, Colorado. This study was conducted to provide hydraulic performance information and demonstrate proof-of-concept for the recommended fish passage structure. The results indicate that a notch in the diversion dam and a downstream 1.5 percent rock channel along the left bank is sufficient to allow adequate passage for the Colorado pikeminnow and razorback sucker, each an endangered fish species, for Colorado River discharges ranging from 640 cubic foot per second (ft^3/s) up to approximately 30,800 ft^3/s. For all cases tested, average mid-depth velocities were found to be between 3.0 foot per second (ft/s) to 8.0 ft/s. Application of the universal velocity profile analysis for a completely rough boundary shows that the turbulent boundary layer is expected to produce velocity zones below approximately 2.0 ft/s within a distance of 0.75-foot from the boundary. Such results are expected to produce efficient passage conditions based on field and laboratory experience, swimming ability of the target species, and behavioral characteristics of the target species

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by
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Denver, Colorado

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Mission Statements

U.S. Department of the Interior

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.

Bureau of Reclamation

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.

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PURPOSE

This report documents the results of physical model investigations associated with developing a fish passage concept for Price-Stubb Diversion Dam (PSDD), located on the Colorado River, near Grand Junction, Colorado. The recommended concept consists of burying the existing diversion dam with a rock structure and providing a fish passage channel that produces passable velocities for Colorado pikeminnow and razorback sucker fish species over a range of river discharges from 640 cubic feet per second (ft^3/s) up to 30,800 ft^3/s. The results of this study identify the hydraulic performance characteristics of the recommended concept and demonstrate proof-of-concept.

APPLICATION

The information included in this report is intended for site-specific application to PSDD. Three alternatives were investigated, and a recommended concept was developed for providing passage for endangered Colorado pikeminnow and razorback sucker species at PSDD. Although these results are site specific, there is potential application to other diversion structures with the same target species and similar hydraulic operating conditions.

INTRODUCTION

BACKGROUND

PSDD is located on the Colorado River, approximately 5 miles downstream from Grand Valley Diversion Dam. The structure is a low-head, run-of-river, concrete diversion dam with an ogee crest and roller bucket energy dissipation apron. The crest elevation is 4721.4 feet, and the apron elevation is 4712.7 feet, producing a drop in elevation across the structure of 8.7 feet, a condition that creates a barrier to upstream passage of endangered Colorado pikeminnow and razorback sucker fish species. Figure 1 is a photograph of PSDD.

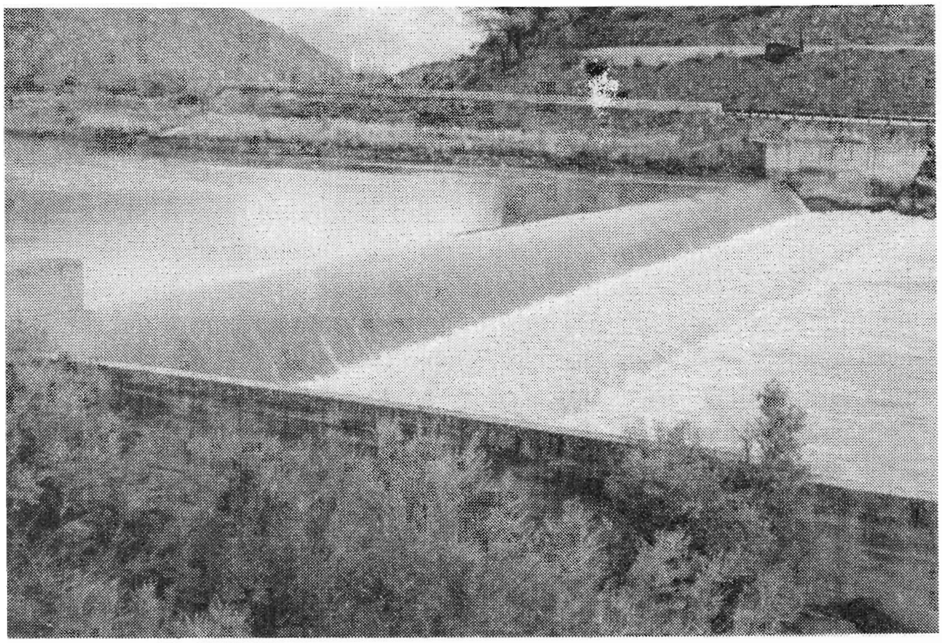


Figure 1. – Price-Stubb Diversion Dam, located on the Colorado River near Grand Junction, Colorado.

The diversion structure has been abandoned (i.e., no diversions are currently being made at this site), and removal of PSDD has been considered as an option. However, the diversion structure, as is, retains some beneficial features because it provides backwater for Ute Water Pumping Plant (located approximately 1,800 feet upstream) and bank erosion protection for both the railroad and highway along the right and left banks, respectively. Hydraulic and Scour Analyses (Collins [1]) were completed by the Bureau of Reclamation's (Reclamation) Technical Service Center to assess the feasibility of removing PSDD. The results indicate that removal would not significantly impact existing bed stability, but would permanently lower the effective water surface elevation at Ute Water Pumping Plant to the extent that pumping would not be possible below a Colorado River Discharge of 4,500 ft^3/s. Based on those considerations, the option of burying the dam represents a viable solution for providing fish passage while at the same time satisfying multiuse needs, including potential hydropower development and boat passage.

PASSAGE CRITERIA

Although limited behavioral and swimming ability data are available for the target species, it is the general perception that both the Colorado pikeminnow and the razorback sucker migrate at specific times of year. The typical annual migration period for the razorback sucker is May through June, while the Colorado pikeminnow has a typical migration period between June and August. Thus, it is critical that adequate fish passage be provided during the period of May through August. The general fish passage criteria for these target species may be summarized as follows:

- The fish passage concept should be sized to accommodate the minimum Colorado River discharge of 640 ft^3/s.
- The fish passage concept should also be capable of providing adequate passage conditions up to the 10 percent exceedence discharge at PSDD during the typical migration period of May through August.
- Average fish passage velocities should not exceed 2.0 foot per second (ft/s) in order to maintain passable conditions for target razorback sucker species.
- Fish passage flow depths should not be less than 1.5 feet.
- The fish passage structure should remain operational year-round.

Figure 2 is the percent exceedence curve that was developed based on hydrologic history (Norval [4]) for the Colorado River near PSDD during the typical migration period. The frequency analysis indicates that to provide fish passage for both target species the passage should be designed to perform adequately up to Colorado River discharges of approximately 30,800 ft^3/s (10 percent exceedence limit that is equivalent to the 10-yr return period). Furthermore, the typical high flow period for the Colorado River corresponds to the typical annual migration period of razorback sucker. Thus, providing adequate passage for the razorback sucker up to the 10 percent exceedence limit during this time period will also be adequate for the Colorado pikeminnow because the latter is considered to be the stronger swimmer.

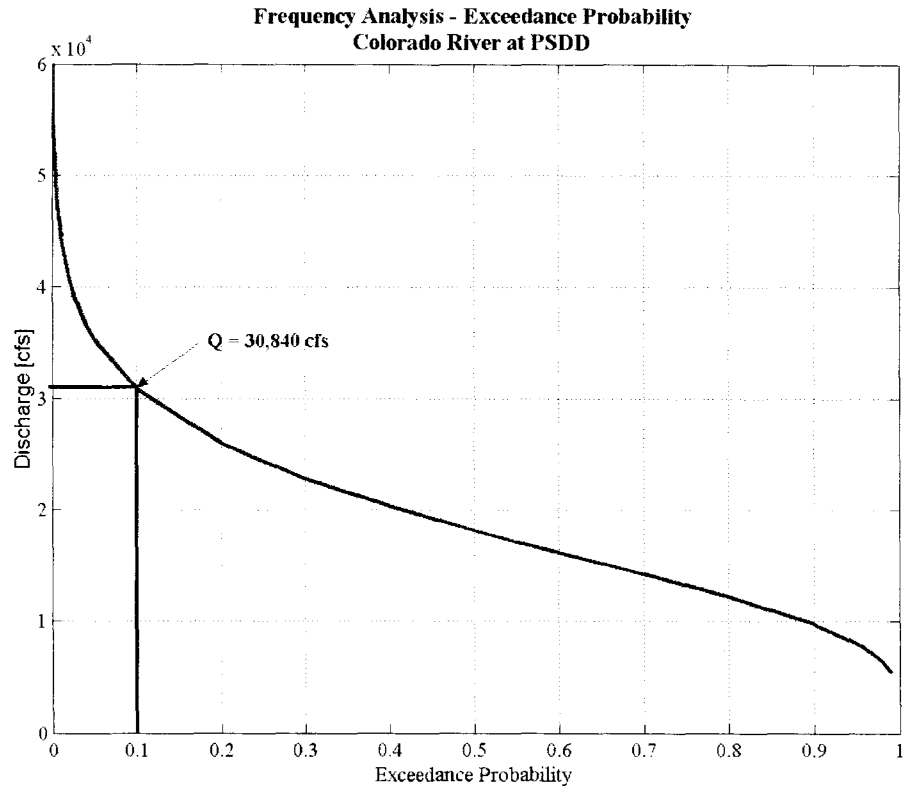


Figure 2. - Frequency analysis for the Colorado River at PSDD showing 10 percent exceedence limit discharge of approximately 30,800 ft^3/s.

HYDRAULIC ANALYSIS

The HEC-RAS model, developed by K.L. Collins [1],was modified to investigate the influence on water surface elevations upstream from PSDD. Configuration 1 is an 800-foot, 2.0 percent rock-ramp structure at PSDD. The results of this configuration are included as appendix A and indicate that the effective control point for the Colorado River at PSDD is the crest for river discharges below approximately 10,000 ft^3/s. Above this discharge, the water surface elevation upstream from PSDD, modified with a rock-ramp structure, begins to deviate from existing conditions. Thus, to some extent, the flood stage upstream from PSDD will be increased slightly with the construction of the fish passage structure because of the change in hydraulic control. The HEC-RAS results included in appendix A give the approximate river stage at various cross sections along the PSDD reach for the rock-ramp structure modification. Table 1 gives the tabulated results at critical locations upstream from PSDD for the Colorado River after the 800-foot rock-ramp structure modification. Table 2 gives the tabulated results for the existing condition.

Table 1. - Water Surface Elevations Upstream from PSDD (obtained using HEC-RAS) for various Colorado River Discharges after modification to the configuration 1 fish passage structure

River Discharge (ft^3/s)	PSDD (ft)	Ute Water Pumping Plant (ft)	Orchard Mesa Siphon (ft)	Cameo Bridge (ft)
640	4722.6	**4722.7**	4722.8	4734.4
8,900	4726.3	**4727.8**	4729.7	4739.5
17,900	4728.6	**4731.4**	4734.4	4742.2
26,800	4730.4	**4734.0**	4738.0	4744.6
35,800	4732.0	**4736.3**	4741.0	4746.8
44,500	4733.5	**4738.2**	4743.7	4748.8
52,800	4734.9	**4739.8**	4746.0	4751.1

Table 2. - Water Surface Elevations Upstream from PSDD for various Colorado River Discharges under existing conditions

River Discharge (ft^3/s)	PSDD (ft)	Ute Water Pumping Plant (ft)	Orchard Mesa Siphon (ft)	Cameo Bridge (ft)
640	4721.9	**4722.2**	4722.3	4734.4
8,900	4724.2	**4727.1**	4729.4	4739.5
17,900	4725.9	**4730.8**	4734.1	4742.2
26,800	4727.3	**4733.6**	4737.8	4744.6
35,800	4728.6	**4735.9**	4740.9	4746.7
44,500	4729.7	**4737.8**	4743.5	4748.8
52,800	4730.7	**4739.4**	4745.9	4751.0

It is important to note that the construction of a rock-ramp structure similar to configuration 1 will raise the water surface elevations upstream from PSDD at Ute Water Pumping Plant. Ute Water does currently experience flooding of their pumping plant during high river flows; hence, any increase in upstream water surface elevation will likely increase the frequency and magnitude of pumping plant flooding. Thus, alternatives that do not increase the upstream stage-discharge conditions are required.

Although this information may be important from a flood stage standpoint and should be considered in the decision making process for this alternative, the primary utility of the HEC-RAS results is the identification of physical model stage-discharge set points.

PHYSICAL MODEL

DESCRIPTION

A 1:20 Froude-scale physical model of PSDD and associated Colorado River topography was constructed at Reclamation's Water Resources Research Laboratory in Denver, Colorado. Figure 3 is a photograph of the model as constructed in the laboratory. The scale was chosen such that a 1,300-foot river reach downstream from PSDD could be included. The model spatial extent includes the full width of the Colorado River along this reach. This approach allowed for adequate spatial extent to investigate rock-ramp alternatives with slopes down to 1.0 percent at prototype Colorado River discharges up to 35,000 ft^3/s.

Figure 3. - Photograph of PSDD physical model as constructed at Reclamation's Water Resources Research Laboratory in Denver, Colorado.

SIMILITUDE

To adequately represent prototype performance, the physical model must achieve geometric and kinematic similarity to the prototype. Geometric similarity is achieved with the ratios of all geometric lengths between the model and the prototype being equal, thus producing similarity in form. Kinematic similarity is achieved with the ratios of all velocities at geometrically similar points being equal. This approach presumes that gravitational forces predominate; hence, kinematic similitude is achieved solely by maintaining equal Froude numbers between model and prototype. The Froude number is defined as

$$\mathrm{Fr} \equiv \frac{\text{Inertial Forces}}{\text{Gravitational Forces}} \equiv \frac{U}{\sqrt{gL}}. \qquad (1)$$

where:
$U \equiv$ characteristic velocity,
$L \equiv$ characteristic length,
$g \equiv$ gravitational acceleration.

Based on this approach, the geometric and kinematic scale relationships are determined as

Geometric
L_r = length ratio = L_p/L_m = 20.0
A_r = area ratio = $(L_r)^2$ = 400.0
V_r = volume ratio = $(L_r)^3$ = 8,000.0

Kinematic
T_r = time ratio = $(L_r)^{1/2}$ = 4.5
U_r = velocity ratio = $(L_r)^{1/2}$ = 4.5
a_r = acceleration ratio = 1.0
Q_r = discharge ratio = $(L_r)^{5/2}$ = 1,788.9

THEORY

Model velocity data acquired near the boundary were used to develop velocity profiles that demonstrate the existence of passable velocities of sufficient extent along the boundaries. The theoretical basis for this approach stems from the semi-empirical universal velocity distribution. Schlicting [5] discusses two cases for which roughness influences the universal velocity distribution: (1) uniformly distributed roughness elements for which similarity is a function of relative roughness only and (2) uniformly distributed roughness elements less densely spaced over a relatively large area for which similarity is a function of both relative roughness and Reynolds number (*Re*). Relative roughness is defined as:

$$\text{Relative Roughness} \equiv \frac{\text{Roughness Height}}{\text{Hydraulic Radius}} \equiv \frac{k}{R_h}. \qquad (2)$$

The ratio of k to boundary layer thickness, in particular the laminar sub-layer thickness, will dictate how the universal velocity distribution is modified from that of a smooth boundary. For a completely rough boundary ($k_s u^*/\nu > 70$), Nikuradse found that the universal velocity distribution is well represented by:

$$\frac{u(y)}{U^*} = 5.75 \log \frac{y}{k_s} + 8.5, \qquad (3)$$

where:
$u \equiv$ Velocity,
$U^* \equiv$ Friction velocity $\equiv (\tau_o/\rho)^{1/2}$,
$y \equiv$ Distance from boundary,
$k_s \equiv$ Equivalent sand roughness.

Then, having two point-velocity measurements within the boundary layer, equation (3) may be written as:

$$u(y_2) - u(y_1) = 5.75U^*[\log(\frac{y_2}{k_s}) - \log(\frac{y_1}{k_s})], \qquad (4)$$

from which the friction velocity is obtained as:

$$U^* = \frac{u(y_2) - u(y_1)}{5.75\log(\frac{y_2}{y_1})}. \qquad (5)$$

Finally, substitution of (5) into (3) gives the logarithmic velocity profile:

$$u(y) = [5.75\log(\frac{y}{k_s}) + 8.5][\frac{u(y_2) - u(y_1)}{5.75\log(\frac{y_2}{y_1})}]. \qquad (6)$$

This approach holds provided the roughness elements are of maximum density or tightly spaced. When roughness elements are less tightly spaced, the appropriate semi-empirical representation of the universal velocity distribution begins to deviate from the above characterization. Schlicting [5] treated regular roughness patterns for various roughness element geometries as an extension to the work of Nikuradse. However, for the purposes of this study, it is sufficient to assume maximum density for roughness elements generated by riprap construction of these types of rock structures. Thus, having two measurements of velocity (i.e., at 0.2 and 0.5 depth) in the vertical, the turbulent boundary layer profile may be estimated using the above universal velocity distribution analysis.

METHODS

The primary objective of this study was to demonstrate proof-of-concept. Such demonstration consists of achieving hydraulic performance for which passable average velocities at or below 2.0 ft/s are realized along the proposed passage structure for the full range of expected hydraulic operating conditions. Velocity measurements were acquired using a Sontek two-dimensional side looking Acoustic Doppler Velocimeter (ADV). At locations where depths were too shallow to use the ADV, a Nixon propeller-meter was employed. Velocity data were acquired at various locations along and across the passage structure at 0.2, 0.5, and 0.8 depths. These data were subsequently used to determine velocity profiles based on the universal velocity distribution for rough boundaries. Structure modifications were made according to the results in order to tune the performance and hence achieve passable velocities.

TESTING

A total of three fish passage configurations were evaluated, all of which represented a variation of the rock-ramp concept. Configuration 1 consisted of an 800-foot-long basic rock-ramp structure producing a constant slope of approximately 2.0 percent. Configuration 2 represented a modified version of configuration 1 to include a riffle-pool substructure, similar to the Grand Valley Irrigation Company Diversion Dam fish-passage structure (Kubitschek, *et. al.*[2]), in an attempt to further dissipate energy and break the overall slope. Configuration 3 was the final configuration tested and consisted of a notch in the diversion dam, an 800-foot minimum left bank rock channel to provide fish passage and a 400-foot lateral rock ramp to convey the remaining river flow. It is important to note that notching the dam not only provides low flow passage, but also reduces the overall slope of the fish passage channel from 2.0 percent to 1.5 percent for the 800-foot length. Figures 4 through 6 represent photographs of the three configurations as constructed in the laboratory. Each of these structures was evaluated under five prototype discharges of 640, 8,944, 17,889, 26,833, and 35,777 ft^3/s. The 640 ft^3/s river discharge represents the instream flow requirements from Grand Valley Diversion Dam located just upstream from PSDD; hence, the minimum hydraulic operating conditions for the fish passage structure. The remaining discharges result from scaling model discharges of 5, 10, 15, and 20 ft^3/s, the latter being the maximum discharge capacity of the model. Stage-discharge relationships were developed from the results of the HEC-RAS model and used to establish flow depths similar to those expected for the prototype downstream from PSDD.

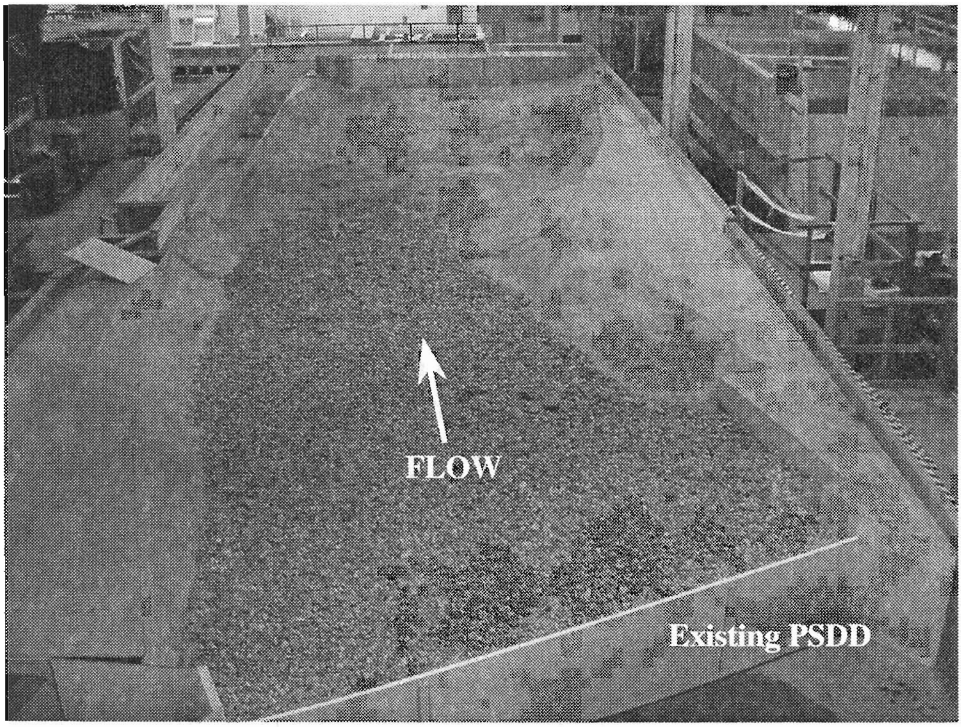


Figure 4. - Configuration 1: 800-foot rock-ramp structure constructed on a 2.0 percent slope.

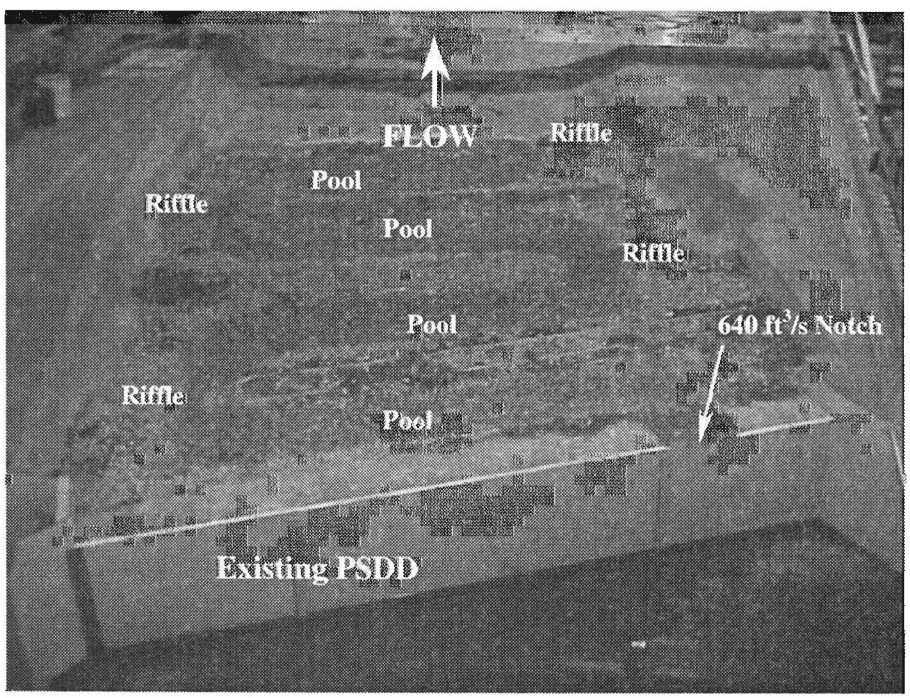


Figure 5. - Configuration 2: 400-foot rock-ramp structure with low-flow notch in diversion dam and riffle-pool substructure.

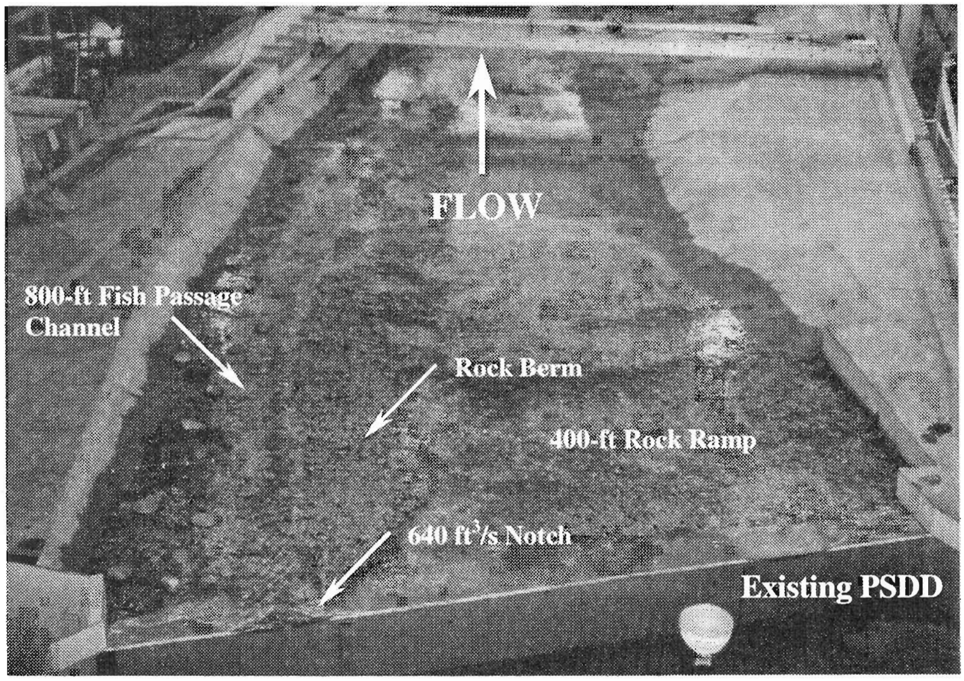


Figure 6. - Configuration 3: 800-foot (1.5 percent slope) fish passage channel along the left bank and a low-flow notch and 400-foot (3.0 percent slope) lateral rock-ramp structure.

RESULTS

CONFGURATION 1: 800-FOOT ROCK-RAMP STRUCTURE

The results indicate that the 800-foot rock-ramp structure produced excessive fish passage velocities for the range of Colorado River discharges tested. Figure 7 represents water surface profiles corresponding to each river discharge condition tested. The results were obtained from flow depth data acquired at various stations along the rock structure. This figure provides an indication of the flow depth verses discharge characteristics of this concept. STA 0 was taken at the crest of PSDD and the rock-ramp structure intersects existing river topography at STA 8. Figure 8 represent velocity profiles obtained from the physical model data acquired at two stations along the rock structure for each Colorado River discharge tested. These results indicate the extent of passable velocity zones near the boundaries. It is apparent that the velocities within 1.5 feet of the boundary are higher than 4.0 ft/s for all cases tested. These results imply that passable conditions will not likely be achieved by this 800-foot rock-ramp structure on a 2.0 percent gradient. In addition to not meeting velocity criteria for the range of Colorado River discharges tested, another deficiency of this structure is that it produces low-flow depth barriers (i.e., flow depths less than 1.5 ft) for Colorado River discharges below approximately 2,500 ft^3/s. Thus, based on these results, it was apparent that a low-flow channel would be required to effectively channelize Colorado River discharges of at least 640 ft^3/s and eliminate the potential for depth barriers. Furthermore, additional modifications are necessary to reduce boundary layer velocities if maintaining a 2.0 percent passage slope is desired.

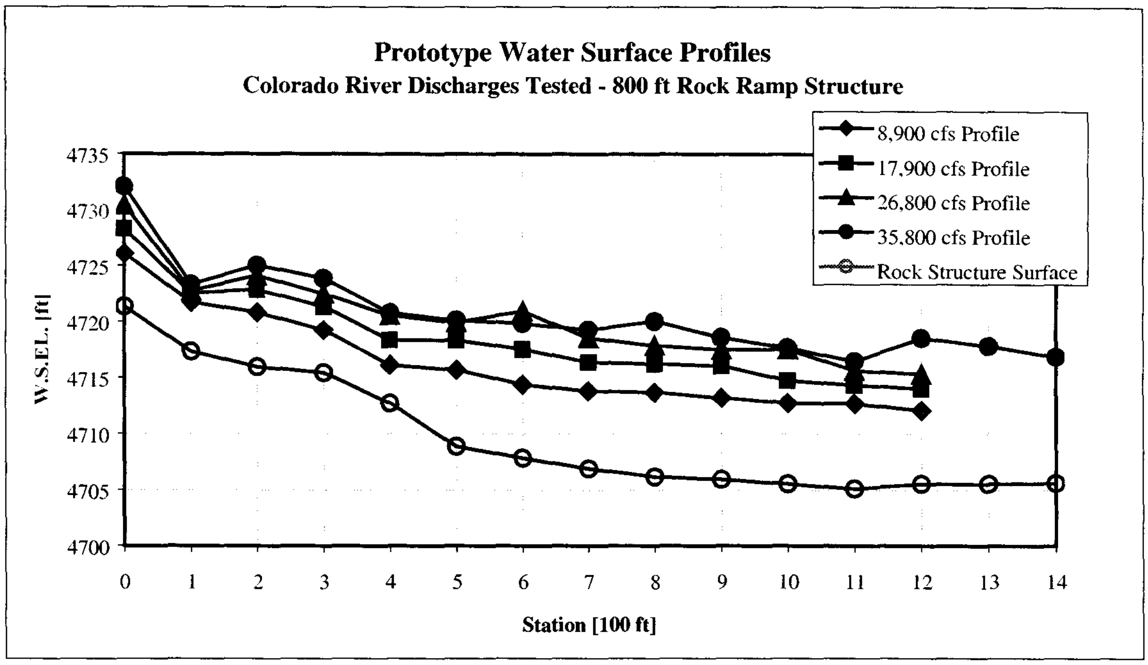


Figure 7. - Prototype water surface profiles for the 800-foot rock-ramp structure (configuration 1) obtained from the physical model study.

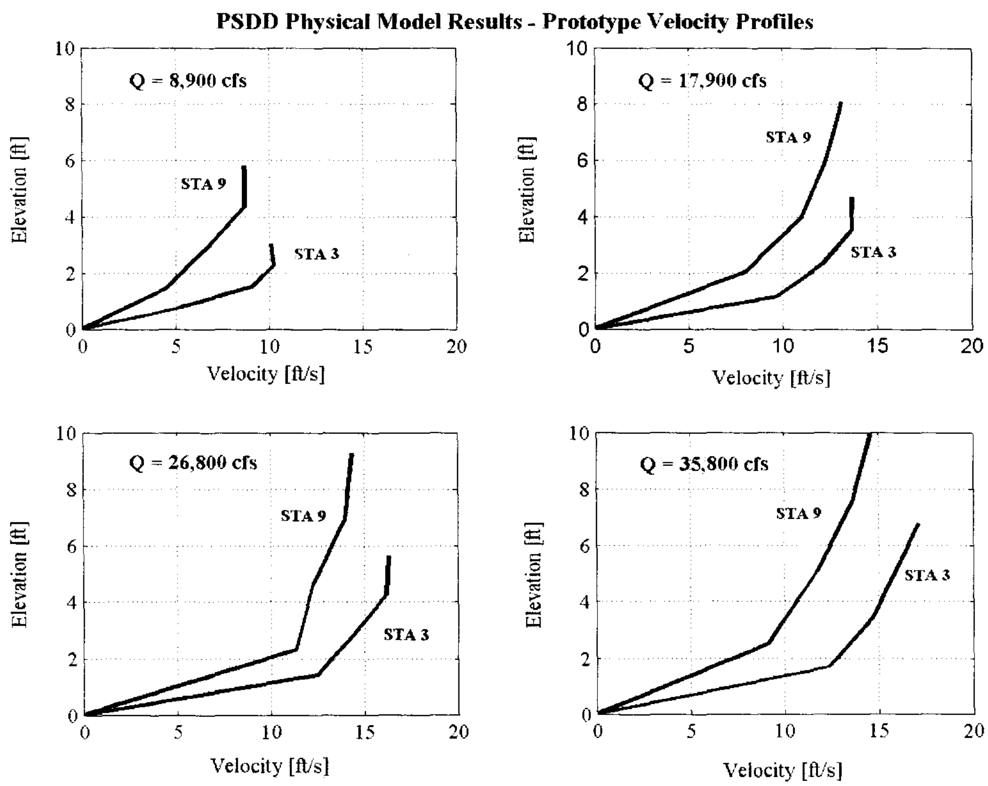


Figure 8. - Prototype velocity profiles (velocity verses distance above bed elevation) for the 800-foot rock-ramp structure for various Colorado River discharges tested.

CONFIGURATION 2: 400-FOOT ROCK-RAMP STRUCTURE WITH RIFFLE AND POOL SUBSTRUCTURE

Based on the results of testing for configuration 1, it was reasoned that the potential for depth barriers could be eliminated by notching the diversion dam. Furthermore, the overall length of the structure could possibly be reduced using a riffle pool substructure to produce a low-flow channel for the minimum Colorado River discharge of 640 ft^3/s, while at the same time producing sufficient energy dissipation to maintain target passage velocities during high-flow conditions. The former feature was achieved, but the boundary layer velocities remained excessive (i.e. > 4.0 ft/s) over a large extent, indicating that the pool configuration did not produce sufficient energy dissipation. This is most likely the result of reduced effectiveness of the substructure at higher Colorado River discharges. In effect, the substructure becomes hydraulically insignificant in contributing to the overall flow resistance of the structure at high unit discharges. It was apparent that passable conditions could not be achieved for the full range of Colorado River discharges required. Furthermore, the riffle-pool configuration is likely to increase construction cost and reduce the level of certainty regarding structural stability.

CONFIGURATION 3: 800-FOOT FISH PASSAGE CHANNEL WITH 400-FOOT ROCK-RAMP STRUCTURE

Configuration 3 showed the best results. Figure 9 represents the water surface profiles acquired along the fish passage channel for the Colorado River discharges tested. Figures 10 through 17 represent results from the mid-depth lateral velocity measurements and indicate zones where velocities are near or below 6.0 ft/s.

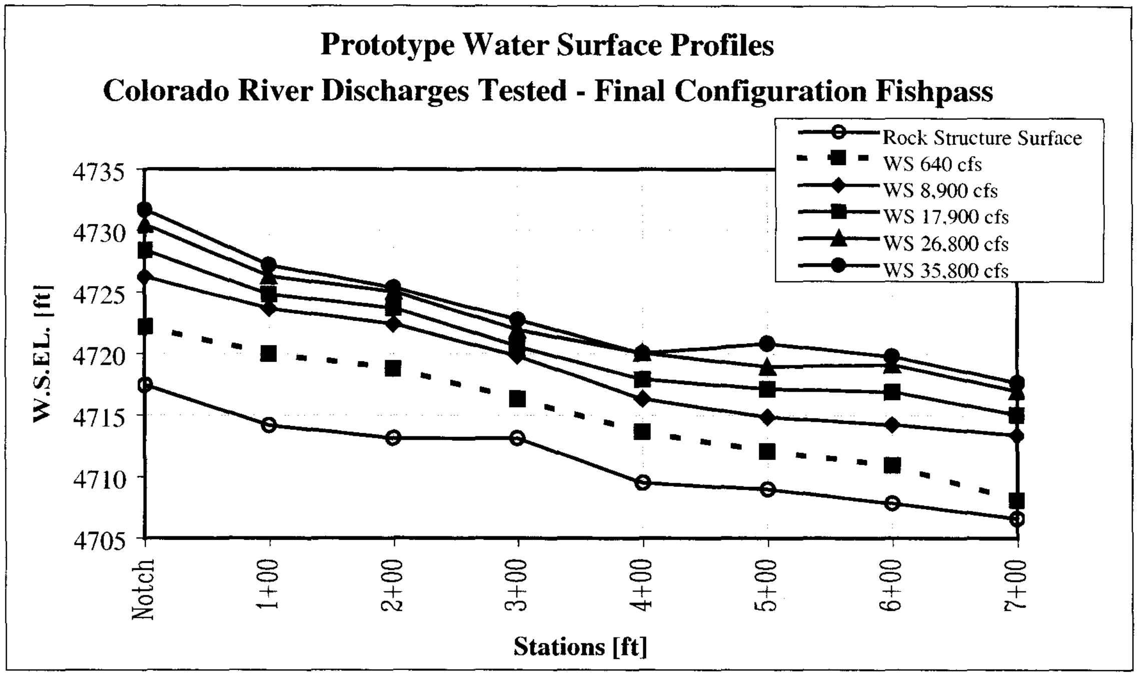


Figure 9. - Prototype water surface profiles for configuration 3 as obtained from physical model.

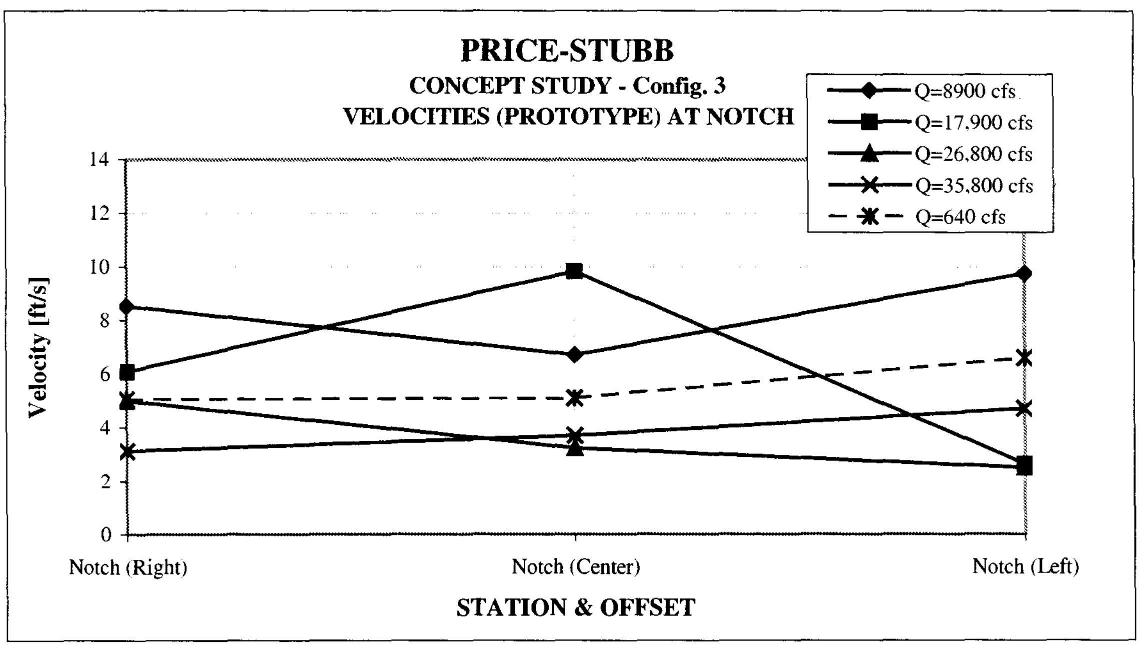


Figure 10. - Mid-depth lateral velocity distributions (looking upstream) at notch (fish passage channel exit) for Colorado River discharges tested.

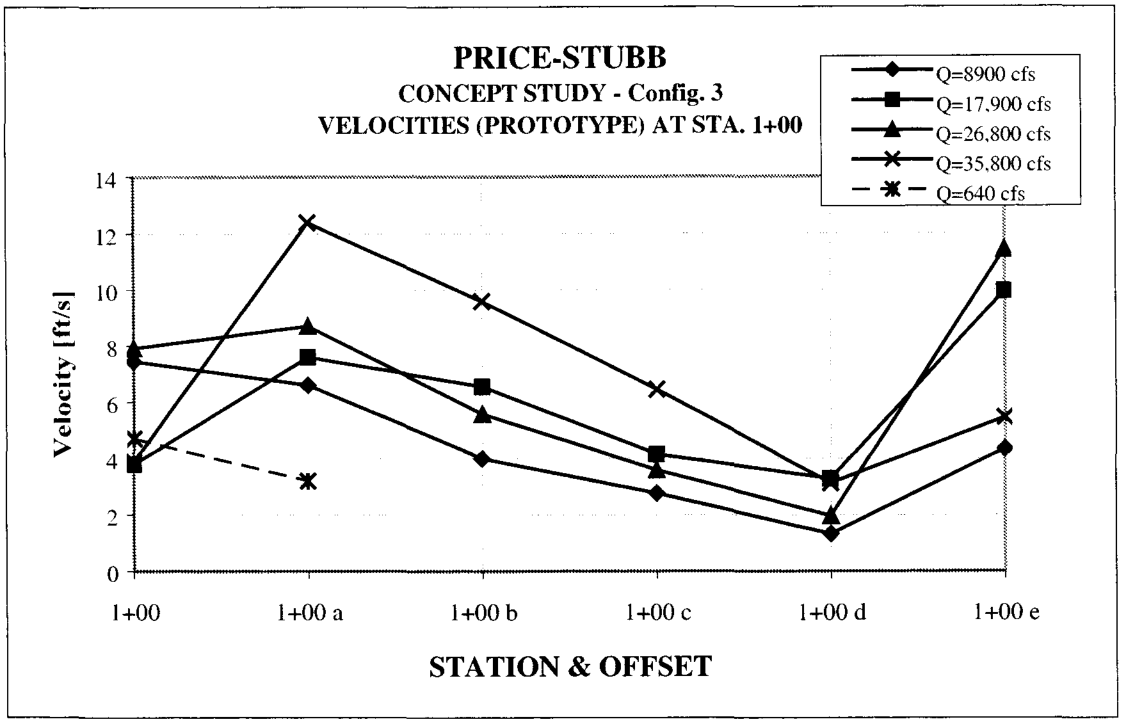


Figure 11. - Mid-depth lateral velocity distributions (looking upstream) at STA 1+00 for Colorado River discharges tested.

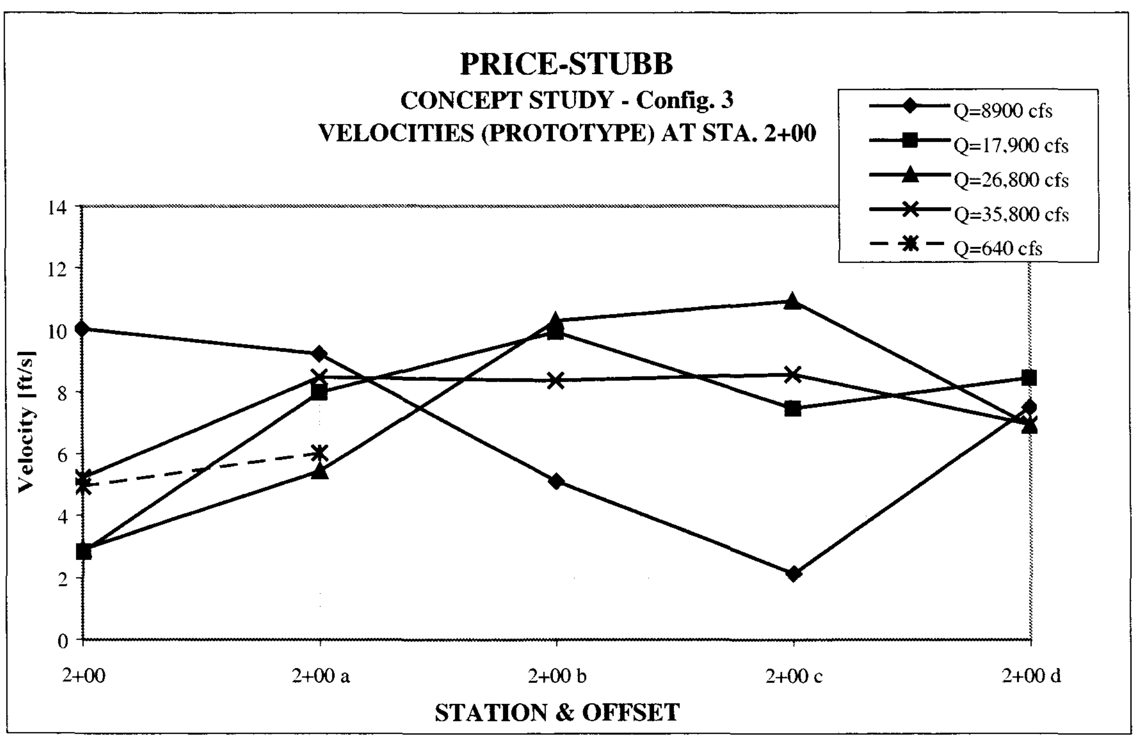


Figure 12. - Mid-depth lateral velocity distributions (looking upstream) at STA 2+00 for Colorado River discharges tested.

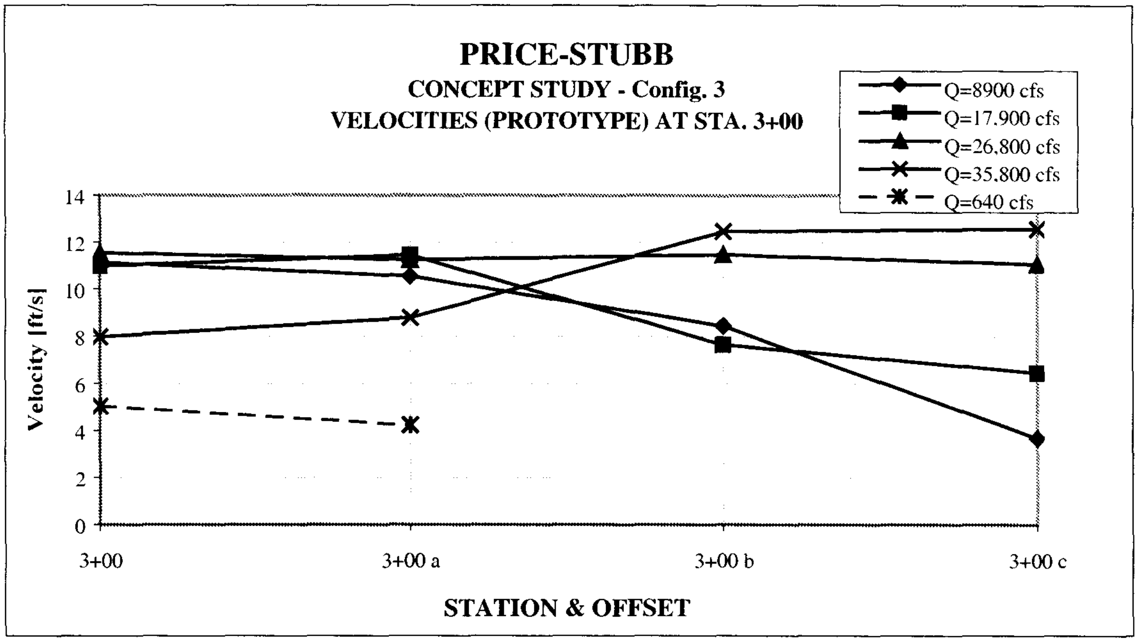


Figure 13. - Mid-depth lateral velocity distributions (looking upstream) at STA 3+00 for Colorado River discharges tested.

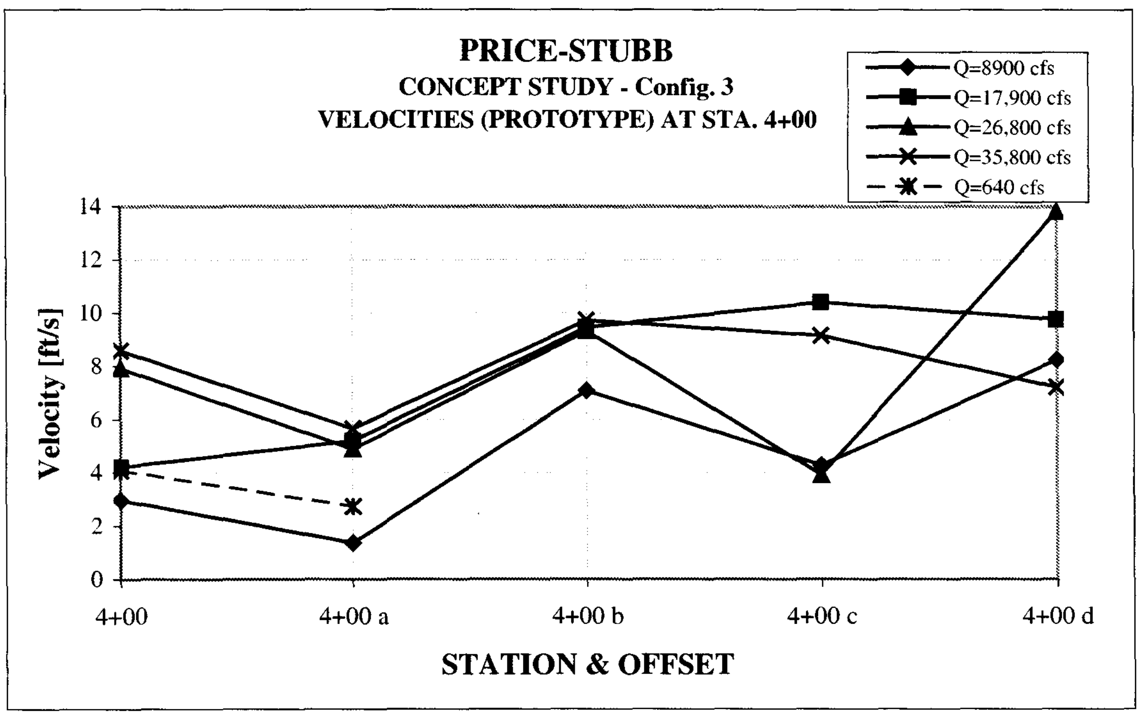


Figure 14. - Mid-depth lateral velocity distributions (looking upstream) at STA 4+00 for Colorado River discharges tested.

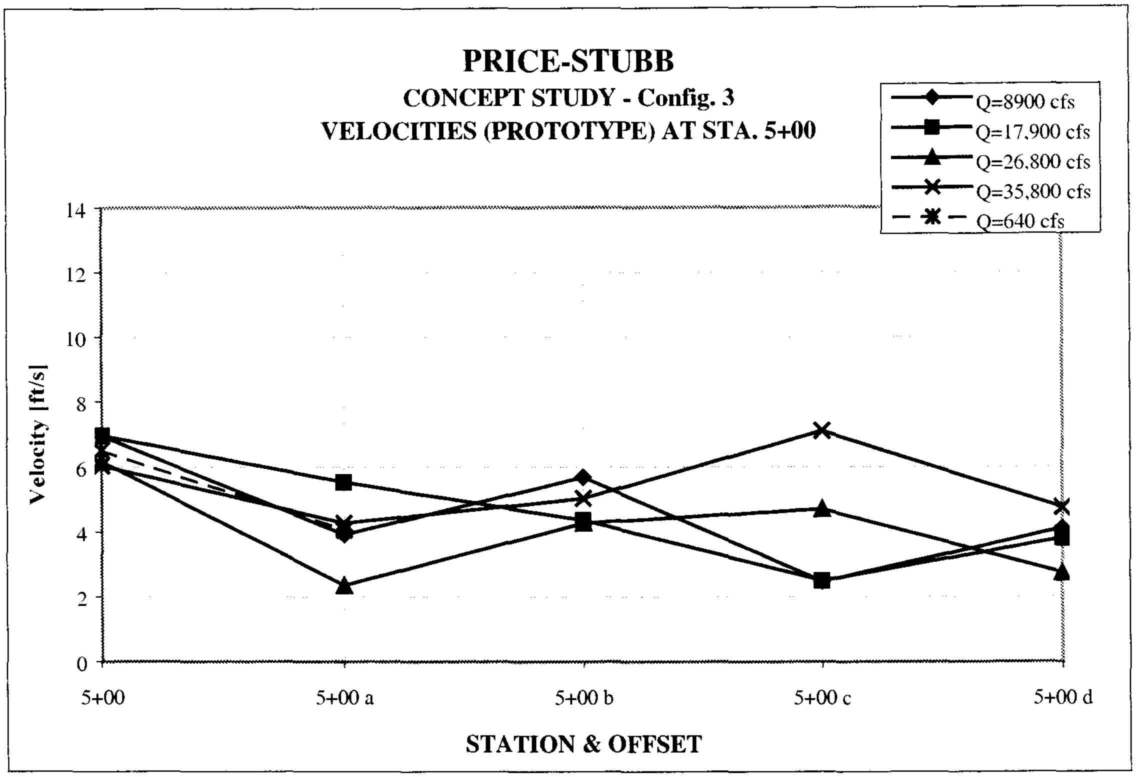


Figure 15. - Mid-depth lateral velocity distributions (looking upstream) at STA 5+00 for Colorado River discharges tested.

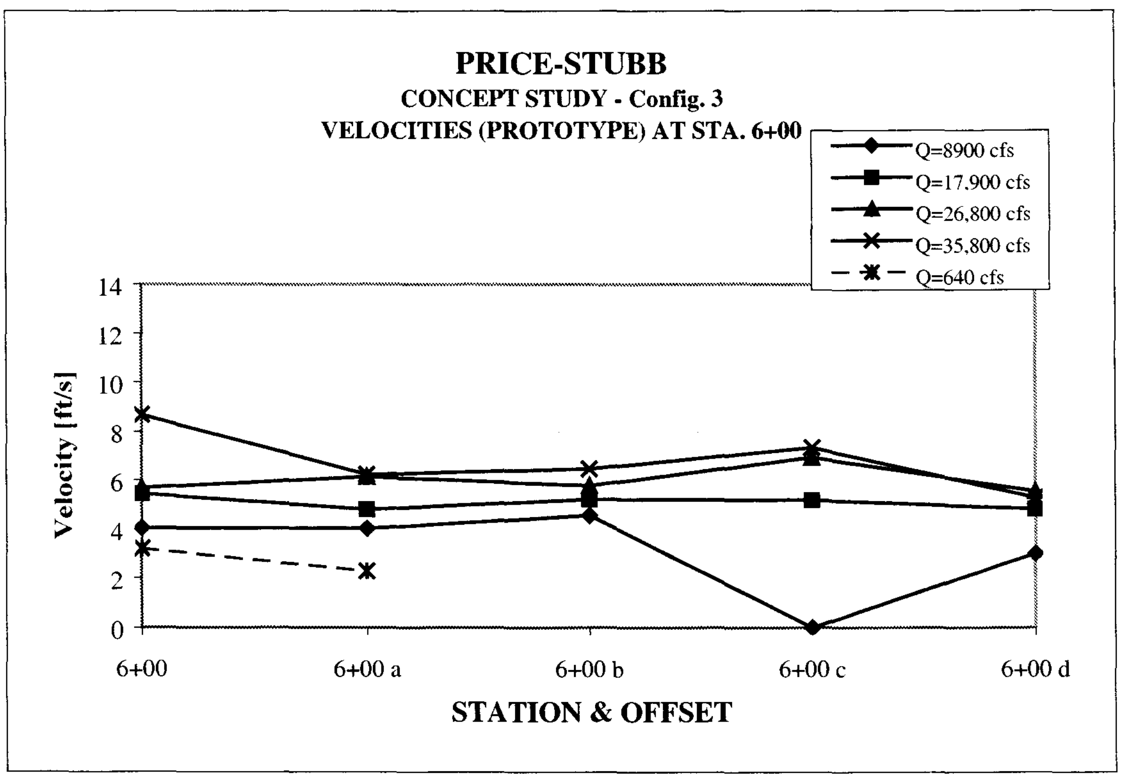


Figure 16. - Mid-depth lateral velocity distributions (looking upstream) at STA 6+00 for Colorado River discharges tested.

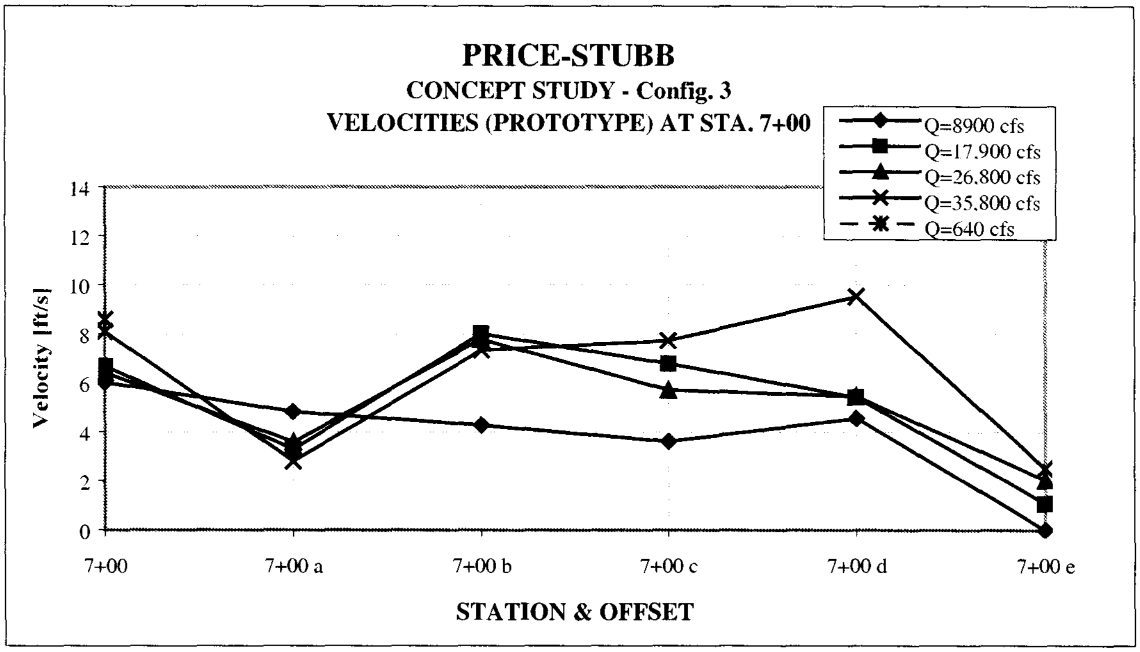


Figure 17. - Mid-depth lateral velocity distributions (looking upstream) at STA 7+00 for Colorado River discharges tested.

Applying the universal velocity distribution analysis here produces results indicating that the low-velocity turbulent boundary layer is of sufficient extent (> 0.75 ft) to achieve target passage velocities of 2.0 ft/s along the low-velocity boundary layer zones. Figure 18 is an example of this result. Taking the roughness height (k) to be 1.5 feet for 16-inch D_{50} material and applying equation (6) for STA 3+00 gives the universal velocity profile (figure 18) for the turbulent boundary layer over a completely rough surface. It is important to note that this velocity distribution is expected to be valid over the full range of discharges tested because, for a completely rough boundary, the turbulent boundary layer velocity profile is independent of discharge (i.e., depends on roughness alone). However, the notch that will constitute the exit of the fish passage structure may require additional treatment because the turbulent boundary layer will not have sufficient length to develop. This problem may easily be handled by extending the exit upstream with little or no gradient. The length of this extension should be that required for the turbulent boundary layer to become fully developed. Furthermore, the extended exit may be widened upstream from the proposed notch geometry to further reduce velocities and increase the rate of boundary layer development. Additional research is being initiated to further define turbulent boundary layer characteristics in the context of rock structures used for fish passages.

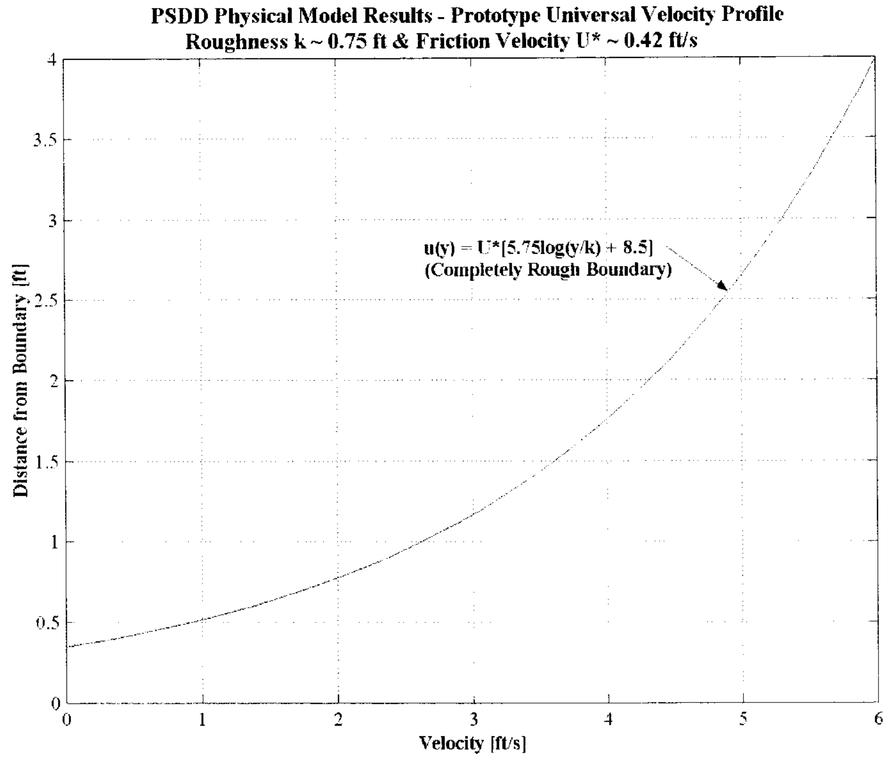


Figure 18. - Universal velocity profile (completely rough boundary). Friction velocity, U*, was obtained from model data and roughness taken for proposed rock size (D_{50} = 16 in).

Another interesting aspect of this concept is that, as Colorado River discharges increase, the velocities along the fish passage channel appear to decrease somewhat. This is most likely the effect of a greater percentage of the flow being passed over the 400-foot lateral rock-ramp as well as backwater effects and the increased resistance caused by increased boundary surface area. Although it was difficult to obtain a detailed description of the influence of large boulders placed along the fish passage channel, qualitative observations showed that the boulders contribute to increased flow resistance and energy dissipation and thereby reduce the average velocities along the fish passage channel and increase the diversity of flow conditions. Furthermore, the widely spaced boulders along the fish passage channel are expected to provide resting zones for migrating fish. An additional feature afforded by this concept is that the berm separating the fish passage channel from the 400-foot lateral rock-ramp structure produces crossing flows at higher Colorado River discharges and allows for continuous access to the low-velocity fish passage channel. Overall, this concept is expected to provide passable conditions for the full range of Colorado River discharges targeted (i.e., 640 ft^3/s up to 30,800 ft^3/s).

The HEC-RAS model was modified to include the fish passage configuration 3 for comparison of the upstream influence of the fish passage structure with existing conditions. The results are included as appendix B and indicate that the effective change in water surface elevation at the Ute Water Pumping Plant is not expected to exceed 0.1 foot above the existing condition for Colorado River discharges of up to 52,800 ft^3/s. The flood-stage at Ute Water Pumping Plant for this discharge will be approximately 4739.4 feet, which is essentially the same as the existing conditions (Collins [1]) and approximately 0.4 foot below the top elevation of the flood protection wall surrounding the pumping plant. The primary reason for the minimal increase is that the modifications to PSDD reflected by configuration 3 do not significantly change the hydraulic control characteristics along the river reach between Ute Water Pumping Plant and PSDD.

Table 3 summarizes the HEC-RAS results at critical locations upstream from PSDD.

Table 3. - Water surface elevations upstream from PSDD (obtained using HEC-RAS) for various Colorado River discharges

River Discharge (ft^3/s)	PSDD (ft)	Ute Pumping Plant (ft)	Orchard Mesa Siphon (ft)	Cameo Bridge (ft)
1,000	4722.0	4722.3	4722.5	4732.3
8,900	4724.0	4727.0	4729.3	4736.5
17,900	4725.6	4730.7	4734.0	4739.6
26,800	4727.1	4733.5	4737.7	4742.5
35,800	4728.3	4735.8	4740.8	4744.9
44,500	4729.5	4737.7	4743.5	4747.1
52,800	4730.5	4739.4	4745.8	4749.1

CONCLUSIONS

- The 800-foot (2.0 percent gradient) rock-ramp structure is not expected to produce adequate passage conditions over the full range of Colorado River discharges targeted (i.e., 640 – 35,000 ft^3/s). Based on physical model results, depth barriers (i.e., depths < 1.5 ft) are likely to occur below approximately 2,500 ft^3/s. Furthermore, the extent of the low-velocity zone near the boundary will not likely be sufficient for passage by the target species.

- Integration of a notch in the diversion structure and a riffle-pool substructure along the 800-foot rock ramp proved to solve the depth barrier problem, but was not effective in increasing the extent of the low-velocity zone along the boundaries above that of the 800-foot rock ramp structure for high Colorado River discharges. Although this structure produced adequate passage conditions below approximately 1,000 ft^3/s, energy dissipation characteristics were insufficient to produce adequate passage conditions above approximately 8,000 ft^3/s. Furthermore, this concept is considered to be more difficult and costly to construct.

- The modified configuration consisting of an 800-foot long (1.5 percent gradient) downstream fish passage channel along the left bank, a 640 ft^3/s low-flow notch in PSDD, a 400-foot lateral rock-ramp structure; and a divider-berm between the fish passage channel and the 400-foot rock-ramp is recommended for implementation at PSDD. The results of the physical model study demonstrated this concept to be adequate in providing a minimum flow depth of 1.5 feet and passage velocities at or below 2.0 ft/s for Colorado River discharges up to approximately 35,000 ft^3/s.

RECOMMENDATIONS

Configuration 3, the modified rock-ramp structure, is recommended for fish passage at PSDD. The recommendation is based on the results of this physical model study. Figures 19 and 20 represent conceptual level design details as plan-view layout and typical sections for the recommended alternative. This alternative provides the advantages of low-flow fish passage at the minimum Colorado River discharge of 640 ft^3/s and high-flow fish passage at discharges of 30,800 ft^3/s. Furthermore, boat passage will probably be available for the full range of river discharges via the low-flow notch at PSDD and the downstream left-bank fish passage channel. In general, boat passage is not recommended for any portion of the structure other than the left bank fish passage channel. However, modifications to the 400-foot lateral rock-ramp structure may be possible to further enhance boat passage features of this concept. Additional functional or multi-use benefits of this structure include maintaining:

- Existing upstream bank-erosion and bed-scour protection.

- Existing upstream water surface elevation at Ute Water Pumping plant.

- Existing head for future hydropower development at PSDD.

- Minimal increase in existing flood stage upstream from PSDD for Colorado River discharges up to 52,800 ft^3/s.

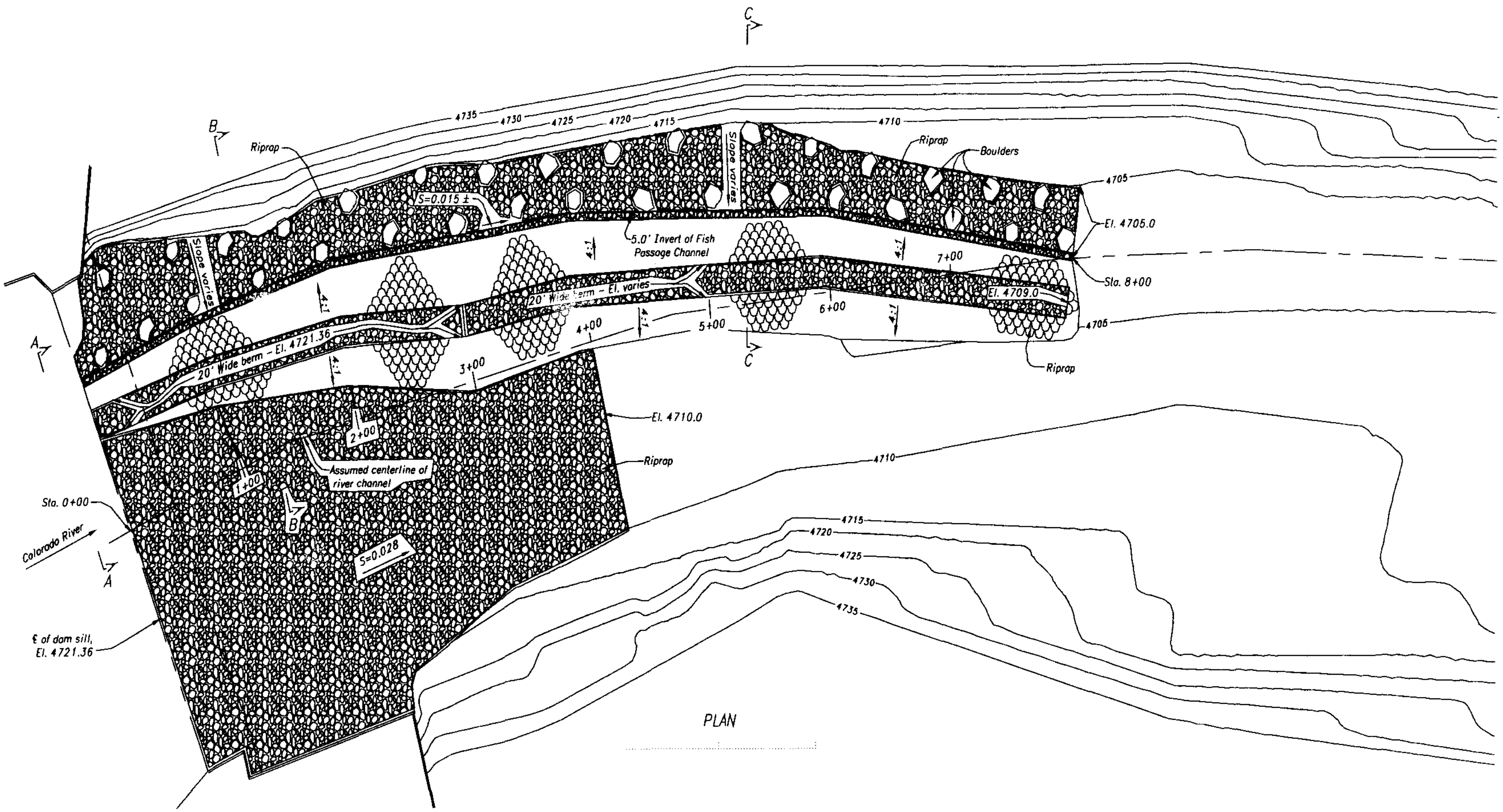
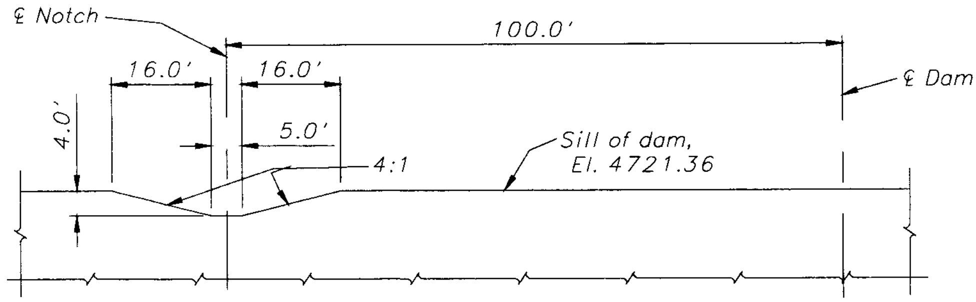
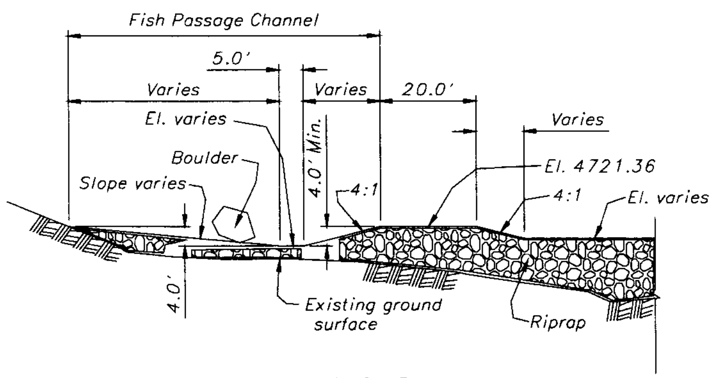


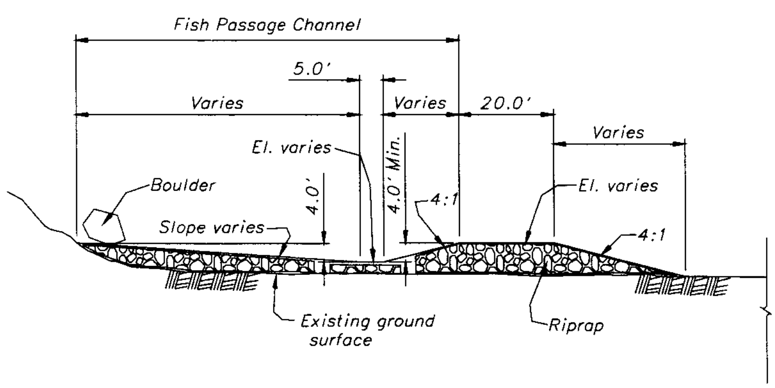
Figure 19. - Recommended configuration (configuration 3) plan view conceptual layout.



SECTION A–A



SECTION B–B



SECTION C–C

Figure 20. - Recommended configuration sections along fish passage structure reach downstream from PSDD.

REFERENCES

[1] Collins K. L. (1999) "Hydraulic and Scour Analysis, Colorado River Near Palisade, Colorado, Price-Stubb Diversion Dam Removal," U.S. Bureau of Reclamation Technical Memorandum dated February 26, 1999.

[2] Kubitschek, J. P. and B. Mefford (1997) "Grand Valley Irrigation Company Diversion Dam Fish Passage Physical Model Study," U.S. Bureau of Reclamation Report No. R-97-06.

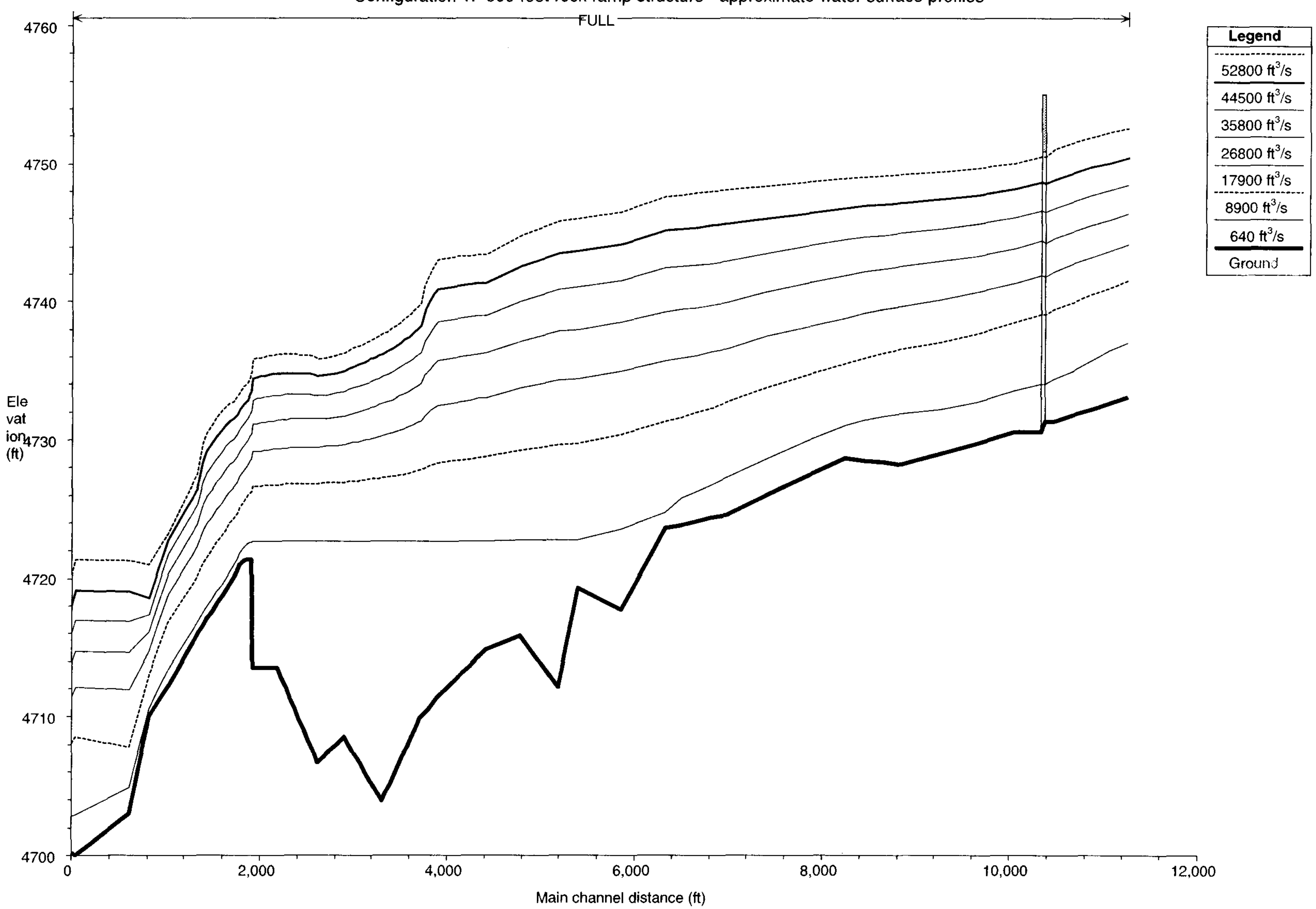
[3] Norval, M. (1998) "Frequency Analysis for the Colorado River at Grand Valley Diversion Dam and Price-Stubb Diversion Dam, Colorado," U.S. Bureau of Reclamation Technical Memorandum.

[4] Schlicting, H. (1979) "Boundary Layer Theory," 7th Edition, McGraw-Hill, Inc.

APPENDIX A

HEC-RAS Results for modified Colorado River reach with Configuration 1: 800-foot fish passage structure at Price-Stubb Diversion Dam. (The HEC-RAS model was developed by K. L. Collins[1] and modified for the purposes of this study. Critical locations for water surface elevation results were identified as Cameo Bridge, Orchard Mesa Siphon, Ute Water Pumping Plant, and PSDD.)

Configuration 1: 800-foot rock ramp structure - approximate water surface profiles



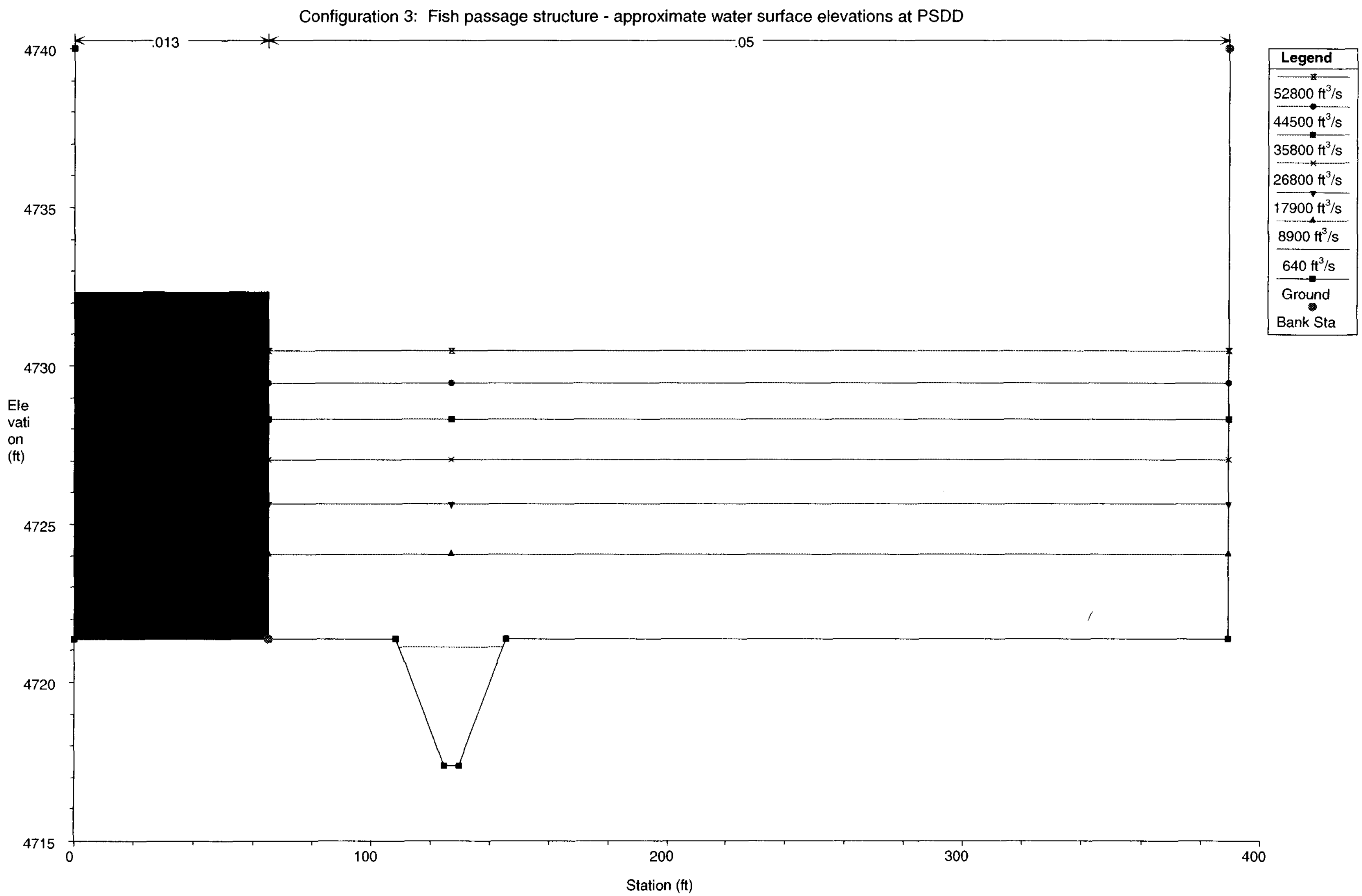
HEC-RAS Results : Configuration 3: 800-foot rock-ramp fish passage structure

River STA	Q Total (ft3/s)	Min Ch El. (ft)	W.S.EL. (ft)	Crit W.S. (ft)	Ch Vel (ft/s)	Flow Area (sq.ft)
46.00	640.00	4731.30	**4734.44**	4733.32	2.48	257.88
46.00	8,900.00	4731.30	**4739.45**	4737.10	5.29	1,682.78
46.00	17,900.00	4731.30	**4742.23**	4738.89	6.70	2,674.83
46.00	26,800.00	4731.30	**4744.61**	4740.29	7.56	3,555.05
46.00	35,800.00	4731.30	**4746.78**	4741.57	8.24	4,363.04
46.00	44,500.00	4731.30	**4748.84**	4742.61	8.72	5,132.37
46.00	52,800.00	4731.30	**4751.12**	4743.54	8.88	5,988.92
Cameo Bridge (STA 45.95)						
45.75*	640.00	4730.52	**4733.56**	4733.66	2.48	258.34
45.75*	8,900.00	4730.52	**4738.51**	4738.90	5.01	1,776.16
45.75*	17,900.00	4730.52	**4741.34**	4741.96	6.30	2,843.05
45.75*	26,800.00	4730.52	**4743.86**	4744.63	7.02	3,823.76
45.75*	35,800.00	4730.52	**4746.12**	4747.02	7.63	4,709.84
45.75*	44,500.00	4730.52	**4748.15**	4749.18	8.12	5,512.86
45.75*	52,800.00	4730.52	**4750.08**	4751.19	8.48	6,276.35
Orchard Mesa Siphon (STA 40)						
40.00	640.00	4719.30	**4722.78**	4722.91	2.86	223.72
40.00	8,900.00	4719.30	**4729.73**	4730.24	5.75	1,549.14
40.00	17,900.00	4719.30	**4734.41**	4735.16	6.93	2,581.40
40.00	26,800.00	4719.30	**4737.99**	4738.95	7.86	3,411.80

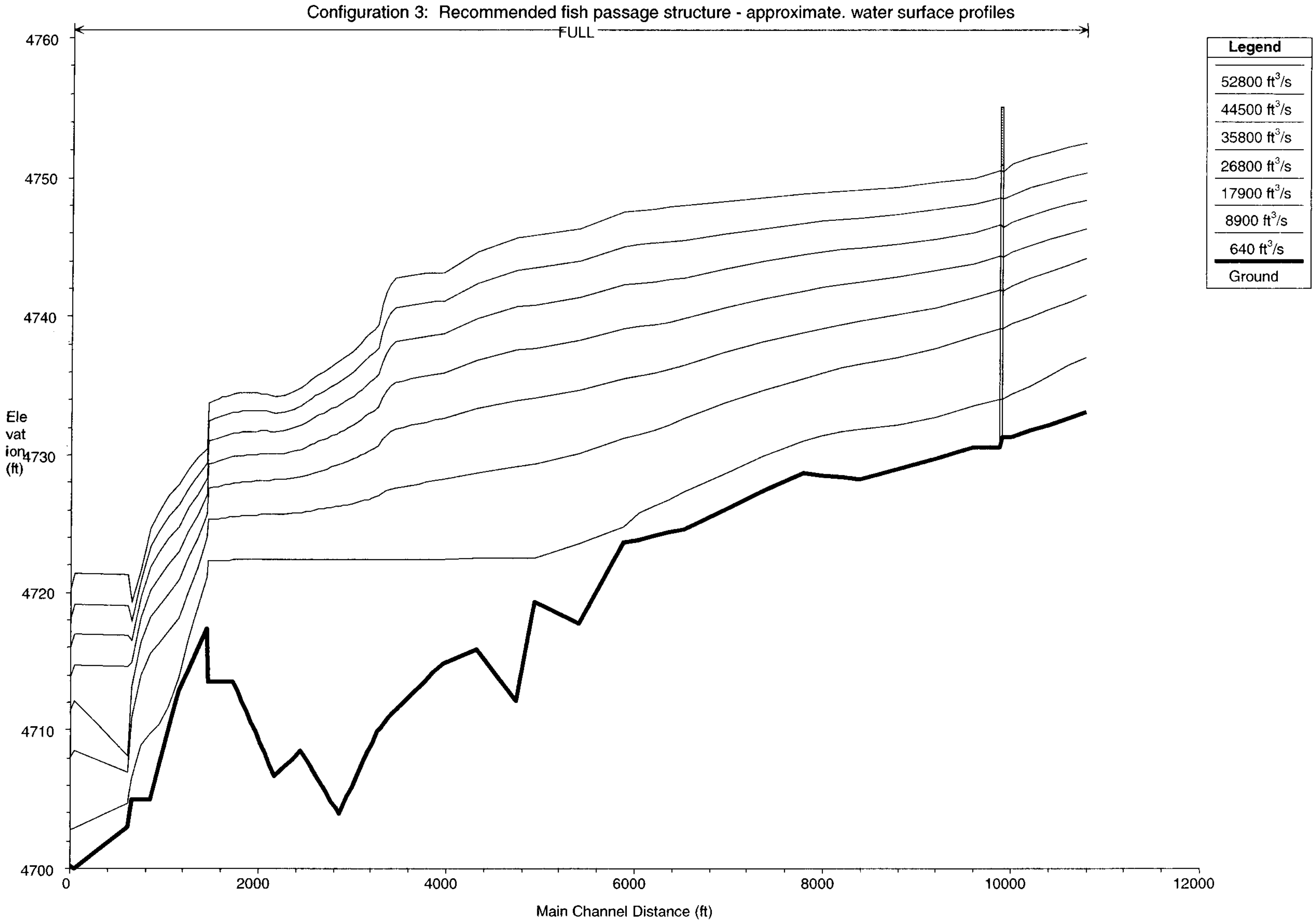
40.00	35,800.00	4719.30	**4741.04**	4742.19	8.62	4,160.63
40.00	44,500.00	4719.30	**4743.67**	4745.00	9.25	4,842.08
40.00	52,800.00	4719.30	**4745.99**	4747.47	9.78	5,463.62
Ute Pumping Plant (STA 35)						
35.00	640.00	4709.90	**4722.68**	4722.69	0.76	843.94
35.00	8,900.00	4709.90	**4727.80**	4728.37	6.07	1,465.09
35.00	17,900.00	4709.90	**4731.35**	4732.66	9.18	1,948.90
35.00	26,800.00	4709.90	**4734.06**	4736.09	11.42	2,347.41
35.00	35,800.00	4709.90	**4736.32**	4739.07	13.31	2,692.17
35.00	44,500.00	4709.90	**4738.21**	4741.66	14.90	2,992.28
35.00	52,800.00	4709.90	**4739.84**	4743.95	16.27	3,257.33
PSDD (STA 29)						
29.00	640.00	4721.36	**4722.61**	4722.65	1.58	405.95
29.00	8,900.00	4721.36	**4726.29**	4726.77	5.58	1,596.11
29.00	17,900.00	4721.36	**4728.58**	4729.49	7.65	2,340.93
29.00	26,800.00	4721.36	**4730.40**	4731.70	9.15	2,930.24
29.00	35,800.00	4721.36	**4732.02**	4733.69	10.37	3,453.10
29.00	44,500.00	4721.36	**4733.51**	4735.44	11.15	4,000.11
29.00	52,800.00	4721.36	**4734.86**	4737.00	11.61	4,513.56

APPENDIX B

HEC-RAS Results for modified Colorado River reach with the recommended configuration, configuration 3: 800-foot fish passage structure with low-flow notch and adjacent 400-foot rock ramp structure at Price-Stubb Diversion Dam. (The HEC-RAS model was developed by K. L. Collins[1] and modified for the purposes of this study. Critical locations for water surface elevation results were identified as Cameo Bridge, Orchard Mesa Siphon, Ute Water Pumping Plant, and PSDD.)



Configuration 3: Fish passage structure - approximate water surface elevations at PSDD
.013
.05
4740
4735
4730
4725
4720
4715
Elevation (ft)
0
100
200
300
400
Station (ft)
Legend
52800 ft³/s
44500 ft³/s
35800 ft³/s
26800 ft³/s
17900 ft³/s
8900 ft³/s
640 ft³/s
Ground
Bank Sta



Configuration 3: Recommended fish passage structure - approximate. water surface profiles
FULL
4760
4750
4740
Ele
vat
ion
(ft)
4730
4720
4710
4700
0
2000
4000
6000
8000
10000
12000
Main Channel Distance (ft)
Legend
52800 ft3/s
44500 ft3/s
35800 ft3/s
26800 ft3/s
17900 ft3/s
8900 ft3/s
640 ft3/s
Ground

HEC-RAS Results : Configuration 3: 800-foot fish passage structure, 640 ft3/s low-flow notch, and 400-foot lateral rock ramp.

River STA	Q Total (ft3/s)	Min Ch El. (ft)	W.S.EL. (ft)	Crit W.S. (ft)	Ch Vel (ft/s)	Flow Area (sq.ft)
46	1,000	4731.3	**4735.11**	4733.7	2.65	377.21
46	8,900	4731.3	**4739.45**	4737.1	5.29	1,682.78
46	17,900	4731.3	**4742.22**	4738.89	6.71	2,670.51
46	26,800	4731.3	**4744.58**	4740.29	7.58	3,544.54
46	35,800	4731.3	**4746.74**	4741.57	8.26	4,348.65
46	44,500	4731.3	**4748.78**	4742.61	8.76	5,109.68
46	52,800	4731.3	**4751.04**	4743.54	8.92	5,961.15
Cameo Bridge (STA 45.95)						
45	1,000	4728.2	**4732.33**	4732.38	1.77	565.81
45	8,900	4728.2	**4736.54**	4736.78	3.93	2,267.36
45	17,900	4728.2	**4739.64**	4740.02	4.95	3,614.00
45	26,800	4728.2	**4742.49**	4742.96	5.5	4,881.32
45	35,800	4728.2	**4744.92**	4745.48	6	5,994.89
45	44,500	4728.2	**4747.08**	4747.71	6.42	6,986.61
45	52,800	4728.2	**4749.11**	4749.81	6.73	7,928.07
Orchard Mesa Siphon (STA 40)						
40	1,000	4719.3	**4722.53**	4722.94	5.17	193.35
40	8,900	4719.3	**4729.3**	4729.88	6.11	1,457.34
40	17,900	4719.3	**4734.09**	4734.88	7.14	2,507.48
40	26,800	4719.3	**4737.73**	4738.73	8	3,350.77

40	35,800	4719.3	**4740.82**	4742.01	8.73	4,107.02
40	44,500	4719.3	**4743.49**	4744.84	9.35	4,792.97
40	52,800	4719.3	**4745.83**	4747.34	9.86	5,419.38
Ute Pumping Plant (STA 35)						
35	1,000	4709.9	**4722.27**	4722.29	1.25	798.82
35	8,900	4709.9	**4726.97**	4727.63	6.56	1,357.71
35	17,900	4709.9	**4730.65**	4732.1	9.68	1,849.81
35	26,800	4709.9	**4733.46**	4735.65	11.87	2,257.5
35	35,800	4709.9	**4735.78**	4738.71	13.72	2,609.48
35	44,500	4709.9	**4737.71**	4741.35	15.31	2,912.52
35	52,800	4709.9	**4739.38**	4743.68	16.65	3,181.47
PSDD (STA 29)						
29	1,000	4717.36	**4721.95**	4721.77	3.63	275.27
29	8,900	4717.36	**4724.01**	4723.95	9.45	942.25
29	17,900	4717.36	**4725.64**	4725.64	12.16	1,471.44
29	26,800	4717.36	**4727.05**	4727.05	13.91	1,927.07
29	35,800	4717.36	**4728.32**	4728.32	15.31	2,338.87
29	44,500	4717.36	**4729.45**	4729.45	16.46	2,703.84
29	52,800	4717.36	**4730.45**	4730.45	17.43	3,029.9