SURVIVAL AND INJURY RATES OF EARLY LIFE STAGES OF FISHES

PASSED OVER THREE DIVERSION SPILLWAY MODELS

FINAL REPORT

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EXECUTIVE SUMMARY

Effects of diversion dam spillway downstream passage on fish are relatively well-
studied for large-bodied or salmonid species but little is known regarding more fragile,
small bodied ($\leq$ 50 mm total length) fish. We assessed survival and injury rates for small
and large size-classes (nominal mean total lengths 25 and 50 mm, respectively) of fathead
minnow *Pimephales promelas* and hybrid rainbow x cutthroat trout (*Oncorhynchus
mykiss* x *O. clarkii*), and small razorback sucker *Xyrauchen texanus*, that passed over
large-scale laboratory models of a 5.7 m high, free-impinging overfall jet (0.023 m^3/s)
with stilling basin depths of 2.5, 15, and 30 cm, a 5.6 m high traditional ogee-shaped
spillway with a smooth face, and the ogee-shaped spillway with energy dissipation steps.
Flows for ogee-shaped spillway experiments were 0.012, 0.02, 0.04, 0.08, 0.16, and 0.24
m^3/s/m. These studies were motivated, in part, by increased use of stepped spillways in
field applications, for which effects on fish are not known. Mean survival proportion of
all species and size-classes, was high in all models (0.97-1.0) under all flow conditions,
except in the overfall jet with pool depth of 2.5 cm (0.78-0.94). Injury rates were also
low for all species and life stages except in the same overfall jet conditions. Survival
rates of small fathead minnows and trout were negligibly lower (0.01) than large ones in
stepped than smooth spillways, and survival was reduced at the highest ogee-shaped
spillway flow rates only for razorback sucker, likely due to poor fish condition. Injury
rates in stepped spillways were slightly higher than in smooth ones, but serious injuries
were rare. Overfall jet spillways caused negligible harm to test fish if sufficient receiving

pool depth was provided. Stepped spillway structures do not appear to cause

substantially higher mortality or injury rates than smooth spillways.

Upstream and downstream movement of fishes in river systems worldwide have been altered due to human-made instream structures (Dynesius and Nilsson 1994; Nilsson et al. 2005). Upstream fish passage over barriers has been studied intensively with a primary focus on adult life stages of anadromous salmonids. Research on downstream fish passage has focused on relatively large-bodied (usually >100 mm total length, TL) juvenile salmon at hydroelectric dams, mostly in western North America (Bell and DeLacy 1972; Ruggles 1980; Bell 1981; Ruggles and Murray 1983; Hackney 1986; Larinier 1987; Clay 1995; Northcote 1998; Mathur et al. 1999). In contrast, effects of downstream passage on other fish taxa, particularly their early life stages, have received only minimal attention.

Because movements are an integral part of the life history of many fishes, and because of prevalence of low-head diversions, a better understanding of effects of spillways on non-salmonid fishes and early life stages may benefit management and conservation activities. For example, adult life stages of some rare cyprinid fishes in streams of the Great Plains in North America move upstream to reproduce, and their passively drifting eggs, larvae, or juveniles may be transported downstream over diversion structures, but effects are unknown (Bestgen and Platania 1991; Fausch and Bestgen 1997; Platania and Altenbach 1998; Dudley and Platania 2007, Bestgen et al. in review).

Lack of available information on downstream passage effects on small (50 mm TL or less) or non-salmonid fishes was a main motivation for this study. Specifically, we estimated survival and injury rates for early life stages for fathead minnow *Pimephales*

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promelas (family Cyprinidae), hybrid rainbow trout *Oncorhynchus mykiss* X cutthroat trout *O. clarkii* (family Salmonidae, hereafter called trout), and razorback sucker *Xyrauchen texanus* (Catostomidae) after passing over a free overfall spillway with a free-impinging jet (pourover jet), a ogee-shaped spillway with a smooth surface (smooth spillway), and a ogee-shaped spillway with energy dissipation steps (stepped spillway). These taxa represent wide-ranging fish families from cold and warm water streams of the western United States and should provide a reasonable representation of the diversity of body size and morphology of fishes where this research applies. Another motivation for this research is recent increased use of energy dissipation steps on diversion dams (Boes and Hager 2003; Baylar et al. 2006), which have the potential to increase fish impacts and injuries. Thus, results reported here may inform managers regarding spillway designs that minimize fish injury and mortality.

METHODS

Test species.—Cultured stocks of fathead minnow and trout were usually available in sufficient quantities and at different times which facilitated testing; razorback sucker were available only once. Although substantial information is available for salmonids, we chose to include trout because little is known about smaller life stages. Because differences in fish size may affect fish behavior and injury and survival rates, we used small and large size-classes (nominally, mean total length [TL] of 25 and 50 mm) of fathead minnow and trout and small razorback sucker in each spillway and experimental condition. Mean length of small fathead minnow, trout, and razorback sucker used in experiments was 22.8, 27.4, and 25.0 mm TL. Mean TL of large fathead minnow and

trout used in experiments was 44.7 and 51.8 mm. Thus, sizes of fish used corresponded reasonably closely to nominal small and large size categories, which were subsequently used as class variables in statistical analyses rather than actual fish sizes.

Model testing, survival and injury studies.—We conducted tests to determine survival and injury rates of small bodied fish passing over three different spillway models in low to moderate flows. Experiments were conducted at the U.S. Bureau of Reclamation, Water Resources Research Laboratory, Denver, CO. Fish were acclimated to test temperatures (16-18°C) over a period of several hours prior to release. The free-overfall spillway test apparatus was a 15 cm diameter pipe with an 8.8 cm-wide rectangular nozzle positioned 5.7 m above a tailwater flume (Fig. 1). All tests were conducted with a flow of 7.1 L/s (0.023 m^3/s). Test discharge simulated a free-overfall flow per unit width of 0.08 m^3/s/m (flow per unit width, or the cubic meters per second flow measured across a 1 meter width) at a brink depth (flow depth at the point the jet leaves the boundary) of about 6.2 cm. The free falling jet maintained a coherent core (jet breakup length, L_b) for a vertical drop distance of about 2.9 m. The jet impacted the tailwater as large, closely-coupled slugs of flow with smaller water droplets on the fringe. A 1.2 m^2 fish capture cage was constructed with a rigid base and 1.5 m-high mesh (1 mm mesh) sidewalls and was positioned in the tailwater flume so that the jet and fish dropped into the cage. A rigid base was used to simulate flow impingement on a concrete apron (usually submerged) downstream of a diversion or other dam. The main treatment effect was to vary the depth of the water (pool depth) in the capture cage at 2.5, 15, or 30 cm, to simulate potential spillway conditions below dams. For each pool depth, dynamic pressure fluctuations (striking pressures due to jet impingement) were measured on the

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cage floor at the center of the jet. Dynamic pressures were expressed as a RMS pressure fluctuation coefficient,

$$C_p = \frac{H'}{(V_j^2/2g)} \, ,$$

where C_p = coefficient of pressure, H' = rms pressure (m of water), V_j = jet velocity at impact (m/s), g = acceleration of gravity (m/s^2). Measured C_p values for the 2.5, 15, and 30 cm pool depths tested were 0.01, 0.004 and 0.004, respectively. The Cp value for 2.5 cm depth compared well with data presented by Ervine et al. (1997; Fig. 2) for rectangular jets of similar fall height (L) to jet breakup length at impact. Increasing the depth to 15 and 30 cm resulted in negligible pressure fluctuation at the boundary.

For survival experiments, a single batch of 10 fish was released into an opening on the top of the overfall pipe 1 m upstream of the jet outlet. About 15 sec after fish were released, flow was stopped and the cage was elevated with a hoist. The cage floor had a low-lipped perimeter that held water and sloped to the middle; water and fish were drained from the cage via removal of a large-bore rubber stopper placed flush with the surface in the center of the floor. Fish in control batches of 10 each were released into the submerged cage and recovered as described above so that effects of fish recovery could be separated from effects of fish passage in the free overfall jet. After capture, fish were enumerated, their condition assessed, and placed in a bag with sufficient water and a headspace of oxygen. Usually 5 batches of fish were used as controls and 10-15 batches were used for treatments at each pool depth, depending on the number of fish available. Fish used in injury studies were released and recovered similarly, except 1-3 larger

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treatment and control batches were used to reduce testing time; we assumed the response of individual fish was independent of one another.

Smooth and stepped spillway tests were conducted using a 0.35 m wide sectional model of an ogee crest spillway 5.4 m-high that sloped 56° from horizontal (1.48 H:1 V) (Figs. 3, 4). At the spillway toe the invert transitioned via a smooth vertical curve to a 3.2 m-long sloping apron into hydraulic jump stilling basin. For all tests, the toe of the hydraulic jump was located approximately 1 m downstream from the sloping apron. Hydraulic jump position was set by adjusting tailwater depth using a downstream gate. For the stepped spillway tests, the smooth spillway was modified by placing eleven 31 cm high steps on the constant slope of the spillway. Twelve steps of increasing height (2.1 cm to 26 cm) were placed on the downstream face of the ogee crest to transition flow onto the steps on the constant slope section. Treatment level flows were 0.012, 0.02, 0.04, 0.08, 0.16, and 0.24 m^3/s/m, (0.13, 0.21, 0.43, 0.86, 1.71, and 2.57 ft^3/s/ft, respectively). Observations of the stepped spillway indicated nappe flow (flow where nearly all water, and presumably fish, impact each step) occurred at unit flows <~ 0.05 m^3/s/m (h$_c$/s <~ 2.3; where h$_c$ = critical depth on the crest, s = step height), which was consistent with the lower three flow levels we tested. A similar estimate of the upper limit of nappe flow can be extrapolated from studies conducted by Matos (2001). At increased levels, flow on the steps transitioned from nappe flow to skimming flow (flow passed over the steps as a coherent stream riding over eddies filling the step offsets, Fig. 5). In the transition regime, as flow increased, a relatively smaller proportion of water impacted the steps and more flow skimmed over the steps (Fig. 6). The onset of full skimming flow can be estimated using Boes and Hager (2003) as:

$$\frac{h_c}{s} = 0.91 - 0.14 \tan\phi ,$$

where φ = spillway slope from horizontal. For our stepped spillway, the Boes formula predicted full skimming flow occurred at a unit discharge of about 0.32 m³/s/m. Thus, full skimming flow was not attained in the model tests. The maximum flow tested (0.24 m³/s/m) passed the steps as about 90% skimming flow, based on observations of the flows lower nappe trajectory and the thickness of the aerated jet (Fig. 7). Average flow velocity at the toe of the spillway upstream of the hydraulic jump was higher for the smooth than the stepped spillway (Fig. 8).

Prior to release of fish in ogee-shaped spillway models, the downstream end of the receiving channel was blocked by a capture net 42 cm wide, 84 cm high, 1 m-deep (2 mm mesh) with a closeable canvas cod end. Batches of 10 treatment fish each were released into the flume at the surface as water passed over the top of the spillway crest. We also released three batches of small fathead minnows on the bottom of the water column with a release tube (Bestgen et al. 2004) at 0.24 m³/s/m and found no effect of surface or bottom release as fish in both treatments had survival of 1.0. Thus, we used surface release for all tests. Control fish were released directly into the standing wave of the receiving channel so that all fish used in tests were subjected to the turbulent downstream flows as well as the capture process. Treatment and control fish were recaptured 30 sec after release by draining water through the downstream gate in the stilling basin. Fish were enumerated, their condition assessed, and placed in a bag with

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sufficient water and a headspace of oxygen. Generally, three batches of 10 fish of each size and species were released at each of the six different treatment flows for survival assessments. A single control batch of 10 fish was released at each flow level; control fish mortality rates at different flows were nearly identical (no difference among flows) and were pooled for presentation. Thus, a minimum of 24 batches of fish (6 controls, 1 batch each per flow level; 6 treatment flows, 3 batches per flow level; total of 24 batches of fish) were used for each species, size, and flow combination for each of the smooth and stepped spillway configurations. Fish used in injury assessments were released and recovered similarly, except 1-3 larger batches were used to reduce testing time.

Fish used in survival and injury assessments were transported in bags in insulated coolers to the Aquatic Research Laboratory at Colorado State University. Fish for survival experiments were acclimated to holding conditions in bags for 1 hr, after which each batch of fish was transferred and held in a 38 L aquarium. Fish survival was assessed post capture, post transport, and at 24 and 48 hr intervals after tests were completed. Some batches of fish in initial tests were monitored for as long as 96 hr, but duration was reduced to 48 hr because mortality due to effects of structures was apparent after 48 hr. Fish were fed flake food and trout chow twice daily during the monitoring period. Cool-white fluorescent lamps were used for illumination (530 lx) and a 12:12-h light:dark photoperiod was maintained.

Injury assessments were made for fish immediately after transport to the lab. Survival of individuals was determined, fish were anesthetized (200 mg/L tricaine methanesulfonate), and injuries were determined by examination with a binocular microscope at 10X magnification using an *a priori* defined set of criteria. Data collected

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included: (1) length, usually as a batch length; (2) eyes: normal, abraded, exophthalmic (bulging), hemorrhagic, missing; (3) caudal, dorsal, and anal fins: normal, frayed, trace fin split (≤ 0.1 proportion of membrane spilt), fin split (> 0.1 of membrane split), broken fin rays (one or more rays disrupted into fragments), missing; (4) bruising: presence, location, and extent; and (5) integument: normal, abraded, cut. Descaling was not assessed because most fish in the size classes used had not yet developed scales (all small fish), or were only partially scaled (large razorback suckers and trout). Longer-term survival assessments for individuals used in injury tests were not useful because examination and handling effects may confound survival rates.

Descriptive and statistical analysis.—Survival rates and presence of physical damage was summarized for each test condition in each of the three spillway models. Mortality of fish in controls, which was presumably due to combined effects of background factors such as pre-experiment fish condition, turbulence in the model, and handling, was used to adjust survival rates for fish in various treatments. We accomplished this using Abbott's formula:

$$p_c = (p_0 - p)/(1 - p),$$

where p_c, p_0, and p, are the corrected, original, and control mortality proportions, respectively (Newman 1995). Abbott's formula is commonly used to correct treatment survival rates in experiments when control animals die, which allows assessment of survival related directly to effects of the treatment, in this case the models and experimental conditions (Bestgen et al. 2004). Thus, observed mortality was presumably

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due to spillway model effects. The adjusted survival proportion $(1 - p_c)$ was compared among species to determine effects of different water depths (free-overfall tests), flow rates (spillways only) and spillway type (smooth vs stepped), and fish sizes (all models). Injury rates for treatment fish were compared directly to injury rates for control fish.

Mean survival (95% confidence limits) and proportion of fish injured were calculated and summary tables constructed. In several cases confidence limits could not be estimated because mortality was zero in all replicates, and subsequently, variance was zero. Because lack of variation in treatments precluded some statistical comparisons, increased emphasis was placed on data analysis by inspection. Non-overlapping confidence limits among treatments were used to indicate important biological effects (Schenker and Gentleman 2001). Because of the large number of fins and injury categories involved in fin assessment, the fin data were re-classified as fins normal or damaged, and then the frequency of fish with one or more damaged fins was calculated. Because many trout had damaged fins due to pre-experiment nipping by other individuals in holding tanks, this metric was not measured in some tests with larger fish.

Survival data for free overfall jet data were also analyzed using Proc Genmod (options link = logit, dist = binomial; SAS Institute 1993) to determine significance of main effects pool depth, fish species, and fish size class. Size class effects (small and large) for fish in the free-overfall tests were limited to fathead minnows because large trout and razorback suckers were not tested in that spillway model. Ogee-shaped spillway data were analyzed similarly for main effects spillway type (smooth and stepped only) fish species, flow rate, and fish size class. We analyzed data and present results for the free-overfall spillway model separate from those for smooth and stepped spillway

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models because treatments (tailwater pool depth in free-overfall vs. flow rate in smooth and stepped spillways) were not comparable.

For smooth and stepped spillway models, size class effects on survival were possible only for fathead minnows and trout because large razorback suckers were not available. After effects of smooth and stepped spillways on survival were understood, we proceeded to test effects of flow rate and size class on survival of fathead minnow and trout. This was accomplished by analysis of covariance (ANCOVA) of survival rates with TL class, flow rate, and their interaction as main effects. Absence of a significant interaction term indicated that trends in survival rates of the two size classes over the different flow rates were similar. A statistical model slope significantly different than 0 in subsequent analyses indicated that flow rate affected survival (a negative slope indicated reduced survival at higher flows), while a model slope not significantly different than zero indicated no detectable change in survival over the different flows. Significant differences between the intercepts for the two lines suggested that survival rate for TL classes was different. Effect of flow rate on small razorback suckers, the only size class tested, was also estimated by determining if the slope of the regression of survival rate as a function of flow rate was significantly different than zero.

Solutions of logistic regression model responses were used to determine differences in survival rates among size classes or at different flow rates. Logit values for survival (S) generated from logistic regressions were transformed to survival proportions by the ratio:

$$e^S/(1 + e^S),$$

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and may be useful to determine the biological significance of survival rates that are deemed statistically significant.

RESULTS

Free-overfall spillway tests

Survival.–A total of 130 batches of control and treatment fish were released in the free-overfall spillway to estimate effects on survival of fathead minnow, trout, and razorback sucker. Among all treatment combinations (species, pool depth, fish size), mean survival (corrected for control mortality by Abbott's equation) was 0.93 (0.78 to 1.0, Table 1). Species and pool depth were important predictors of fish survival but fish size was not (Table 2). Survival was relatively lower (0.78 to 0.94) for all species at a pool depth of 2.5 cm. Survival rates for all species at pool depths of 15 or 30 cm was 0.97 to 1.0. Because survival of larger fathead minnows was 0.98 at both the 15 and 30 cm pool depths, and because of relatively high survival of all species at 15 cm pool depth (≥ 0.98), we did not conduct tests for other species or life stages at the 30 cm pool depth.

Survival of all species in small size-class fish was 0.78 to 0.94 in tests with a pool depth of 2.5 cm; confidence limits among species overlapped. Trout in control releases with a pool depth of 2.5 cm survived at a relatively low rate (0.92).

Injury.–Injury rates were generally low for most species and treatment combinations in the free-overfall spillway model (Table 3). The proportion of fish with 1 or more fins damaged was higher at the 2.5 cm pool depth (0.22) compared to controls

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(0.04). Fin damage rates were usually higher for treatment fish than controls at all pool depths but only modestly so, and most damage consisted of minor splits in the fin membrane. Extensive fin damage in all trout, presumably due to fin nipping in culture tanks, precluded additional assessments. Bruises were detected at slightly higher rates for treatment fish than controls, and rates were slightly higher in 2.5 cm deep pool tests compared to 15 cm. Integument damage was relatively low, except for trout in 2.5 cm deep pool tests (0.06). Injuries detected were generally not considered fatal, with the exception of trout (0.1) in tests with the 2.5 cm deep pool, and the mortality rate was similar to that observed in survival tests (0.065, reported above).

Smooth and stepped spillway tests

Survival.—A total of 250 batches of fish (control and treatment, Tables 4 and 5) were released to test effects of the smooth and stepped spillways on survival of fathead minnow, trout, and razorback sucker. A single batch of fish (small fathead minnow at 0.24 m^3/sec in the smooth spillway) was excluded from analyses due to abnormally low survival (0.3), presumably due to unusual handling or disease effects; the other two batches in the same treatment survived at the same rate as controls (0.9).

Among all treatment combinations (species, smooth or stepped, spillway, spillway flow rate, and fish size), mean survival was 0.98. Over all flow rates, inspection of data showed that small fathead minnow survival was slightly lower in smooth spillway tests (mean = 0.94, 0.87-1.0) than in stepped spillway tests (mean = 0.98, 0.97-1.0); survival of large fathead minnows was equal and high (mean = 0.995, 0.97-1.0) in each spillway model. Survival of small and large trout exceeded 0.99 in both smooth (means

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> 0.99, 0.97-1.0) and stepped (means > 0.99, 0.93-1.0) spillway models. Mean survival rate of razorback sucker survival was 0.975 in the smooth spillway (0.91-1.0) and higher than mean survival observed in the stepped spillway (mean = 0.91, 0.81-0.99).

Logistic regression results supported the notion that survival rate of all species was not significantly different in smooth and stepped spillways (df = 1, Chi-square = 2.39, p = 0.1223, Table 6). The slightly positive (higher survival) but statistically non-significant parameter for smooth spillways in the overall model was due to lower survival of small razorback suckers in the stepped spillway.

The reduced statistical model without main effect spillway type indicated that size class, species, and spillway flow rate were the most important main effects (Table 7). The ANCOVA's for fathead minnow and trout did not show a significant flow rate x fish TL class interaction (p > 0.05) which allowed us to proceed with analysis of main effects of flow rate and fish size. The ANCOVA for fathead minnow showed a slightly negative but non-significant effect of flow (df = 1, chi-square = 2.21, p = 0.1372), indicating that survival rates were similar across flow rates from 0.012-0.24 $m^3/s/m$. The analysis also demonstrated that small fathead minnow had a statistically significantly higher mortality rate than larger ones (df = 1, chi-square = 6.58, p = 0.01). However, survival rates for small (0.99) and large (0.995) fathead minnows were nearly identical and the significant test simply reflected the large sample size available to detect small effects in the statistical model.

The ANCOVA for trout also showed a statistically non-significant effect of flow rate (df = 1, chi-square = 0.25, p = 0.6175) and only a marginal effect for TL class (df = 1, chi-square = 2.82, p = 0.0933). Lack of a flow effect indicated trout survival was

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similar across flow rates. Model solutions showed that small trout (0.984) had only slightly lower survival rates than large trout (0.995).

Razorback sucker data showed a significant and negative effect of flow rate on survival ($df = 1$, chi-square $= 5.29$, $p = 0.0214$). Model solutions showed that razorback sucker survival at the lowest flow was 0.97 compared to 0.89 at the highest flow.

Injury.—Injury rates were generally low for most species and treatment combinations in both smooth and stepped spillway models (Tables 8 and 9). When injuries were detected, rates were modestly higher at low flow levels (0.012 and 0.08 $m^3/s/m$) than for high flows (0.24 $m^3/s/m$) for all species (e.g., small fathead minnow). Recall that treatment injury rates were not adjusted by controls in these tests.

Injury rates for small fathead minnows were higher in the stepped spillway than the smooth, except that fin damage was slightly higher in the smooth spillway. Fatal injury rates to fathead minnows were slightly higher in the stepped spillway than in the smooth, but overall, severe injuries were rare.

Trout injuries were also slightly higher in the stepped spillway than in the smooth, particularly for bruises. Bruising rate in smooth spillway control fish was comparatively high and similar to treatment fish, which should lead to the conclusion of no effects from the structure. Integument damage rates due to passage were about equal in each model type, and overall were very low, considering the relatively high incidence in control fish. Trout fin damage was high in all treatment and control fish, again owing to apparent nipping by other fish. Fatal injury rates to trout were slightly higher in the stepped spillway than in the smooth, but amounted to only a single mortality in the stepped spillway compared to none in the smooth spillway.

Incidences of injuries to razorback sucker were also slightly higher in the stepped spillway than in the smooth spillway, particularly for bruising. However, fin damage rates for razorback sucker were higher in the smooth spillway than in the stepped spillway.

DISCUSSION

Survival rates.—Survival rates of fish were high in most tests, regardless of spillway type, fish species and size, and pool depth or flow rate. The exception was relatively low survival rates in free-overfall spillway tests with RMS pressure fluctuation coefficients of about 0.01 (pool depth of 2.5 cm). Survival was higher at pool depths of 15 and 30 cm in free-overfall spillway treatments because jet breakup (L/L_b value of about 2) produced negligible jet impact with the cage floor.

The relatively high survival rates we found for fathead minnow, trout, and razorback sucker in the pourover jet spillway, with the exception of those in the shallow pool condition, were consistent with those noted in other studies that mostly used larger fish (Bell and DeLacy 1972; Ruggles and Murray 1983). For example, Schoeneman (1959, citation from Bell and DeLacy 1972) found 97 to 100 % survival for Chinook salmon *Oncorhynchus tshawytscha* and silver salmon *O. kisutch* 75 to 100 mm in length (type of length measure not reported) that experienced a 7.9 m free fall at 8.8 to 14.9 m/sec velocity into a capture net located in a deep spill basin. Survival of control fish was 100%, so mortality attributable to the drop was up to 3%. Survival of 75-178 mm rainbow trout *O. mykiss* and silver salmon was 98.5 to 99.7% after being dropped from a helicopter 91.4 m above the water surface (Regenthal 1956, from Bell and DeLacy 1972);

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control fish survival was 100%. Richey (1956, from Bell and DeLacy 1972) found that relatively small-bodied fish 102-127 mm reached a terminal velocity of about 16 m/sec, while heavier fish had much higher terminal velocities. Most free fall experiments with relatively small fish showed low mortality (about 2% or less) because terminal velocities (up to about 16 m/sec) were apparently less than lethal impact velocities (Ruggles and Murray 1983). In general, fish survival in free fall jet tests for relatively small-bodied fish that we tested were similar to or higher than survival rates for larger bodied fishes, suggesting that early life stages were resilient.

The high survival rates reported from the literature above assume fish do not strike fixed objects, as mortality and injury rates under those conditions were much higher (e.g., Hamilton and Andrew 1954, partial reference in Bell and DeLacy 1972). Impact mortality rates may be affected by depth of the receiving pool, as we found reduced fish survival in our free fall jet tests with the 2.5 cm pool depth. This was similar to the findings of Graser et al. (1979), who surmised that reduced downstream density of catostomids and particularly, small shad larvae, was caused by passage over a detention dam, where flow (and presumably fish) struck concrete dissipation ledges after passing the dam crest. Greater receiving pool depths may reduce impact mortality rates, as our relatively low flow tests showed low fish mortality when receiving pool depths were 15 cm or greater and C_p was low.

A main comparison of interest in this study was whether ogee-shaped spillways with steps caused higher mortality than traditional smooth surfaced spillways for early life stages of fish. Stepped spillways operating in nappe flow or transitional regimes have substantial flow that impacts spillway steps, increasing potential for higher injury

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compared to a smooth structure. Fathead minnow and trout survival in the stepped spillway was equal to or higher than that measured in the smooth spillway. Razorback sucker survival was slightly lower in the stepped spillway (0.81-0.99) than the smooth spillway (0.91-1.0), but we feel those tests were somewhat confounded by reduced health of fish used in stepped spillway experiments. Reduced health of razorback suckers was indicated by observations of weak swimming ability and low survival rate of control fish (0.9) in stepped spillway tests compared to survival of control fish (0.98) in smooth spillway experiments, which were slightly larger at testing. Thus, the hypothesis that small-bodied fish survival would be reduced in a stepped spillway compared to a smooth one was not supported.

Fewer comparative studies were available to understand survival of fish passing over ogee-shaped spillways. Schoeneman et al. (1961) estimated 95% survival of fingerling (45-60 mm) and yearling (95-145 mm) Chinook salmon in releases at McNary and Big Cliff dams, which had an ogee-shaped spillway and terminal (bucket) jump. High survival rate of Chinook salmon in that study was similar to survival rates we found for small-bodied fathead minnow, trout, and razorback sucker in our study. Differences in spillway construction material may affect survival rates because severe injuries from rough concrete used for river spillways may be more frequent than from the smooth plywood surface used in our spillway models. Thus, definitive literature comparisons are not possible at this time.

Mortalities in smooth spillway tests were few likely because flow at the bottom of the ogee-shaped spillway followed a continuous and smooth transition to a sloping apron hydraulic jump stilling basin. A long basin without flow disruption devices (chute blocks

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or floor blocks) was used in the tests. Thus, fish were largely only subjected to shear and flow turbulence associated with the action of the hydraulic jump. Shear impacts described by Neitzel et al. (2004) were not detected likely because flow velocities and associated strain rates generated in all spillway models in this study did not exceed the critical threshold for injury.

We expected mortality differences to be greater in both ogee-shaped spillways at higher flows for all species because of the extreme turbulence and higher velocities compared to more benign conditions at lower flows. These perceptions were incorrect. Experiments showed only a minor effect of flow rate on survival because only small fathead minnow and health-impaired razorback suckers had slightly lower survival at the highest flows in the stepped spillway.

Injury rates.— Injury rates in our experiments were relatively low as were injuries that were likely to cause mortality except in the free-overfall spillway model with pool depth of 2.5 cm. Higher bruising rates in the free-overfall spillway were evident for both fathead minnows and trout in the 2.5 cm depth treatment than for control fish, as was fin damage for small fathead minnow, likely because the slight water depth was insufficient to produce deceleration and reduce fish contact with the cage floor.

Injury rates were slightly higher for fish in the stepped spillway than in the smooth spillway, but differences between treatment and control fish were typically small. An exception was higher bruising rates in stepped spillway for razorback suckers, which were not healthy at testing. Although we have no substantiating observations, perhaps impaired fish had reduced swimming ability that induced higher rates of impact to the

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model and more bruising than for healthy fish. Higher fin damage rates of razorback suckers in smooth spillway fish compared to that in the stepped spillway is inexplicable.

We also observed slightly higher bruising and eye injury rates in the stepped spillway at the lowest flow compared to higher flows. This might be reasonable because fish likely impacted flow disruption steps during nappe or transition flows more often as they traveled down the spillway. Although we have no direct observations of impacts, we surmise this scenario is true because at low flows most water hits the steps but at higher flows, much of the water mass appears unimpeded by the flow disruption steps as it skims down the flume surface. That we did not observe reduced survival in the stepped spillway at low velocities was likely due to relatively low velocities and a water pillow that cushions impacts of fish on the step.

Few other studies assessed injury rates in experimental conditions that were similar enough to ours to allow useful comparisons and none were with small-bodied fish. Johnson et al. (2003) studied injury effects of jet entry on small (87-100 mm fork length) and large (135-150 mm) juvenile Chinook salmon. They did not detect injuries at fish entry velocities of 12.2 m/sec or less, which were in a range similar to that used in our free-overfall jet studies. Similarly, Neitzel et al. (2004) did not detect injuries or mortality for rainbow trout, Chinook salmon, and American shad *Alosa sapidissima* exposed to shear environments that produced strain rates in the range of our test conditions.

We conclude that survival of all species and size-classes, and under all flow conditions, was high in all models, except in the overfall jet with pool depth of 2.5 cm. Injury rates were also low for all species and life stages except in the same overfall jet

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conditions. Injury rates in stepped spillways were slightly higher than in smooth ones, but serious injuries were rare. Overfall jet spillways caused negligible harm to test fish if sufficient receiving pool depth was provided. Stepped spillway structures similar to those we tested do not appear to cause substantially higher mortality or injury rates than smooth spillways.

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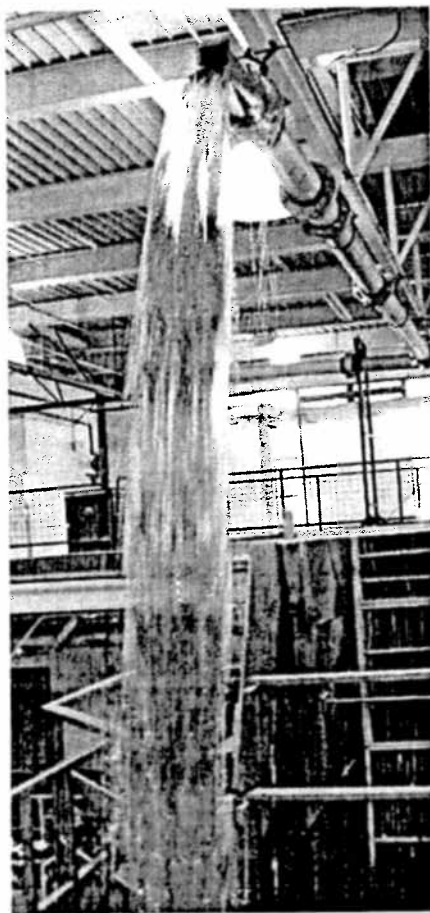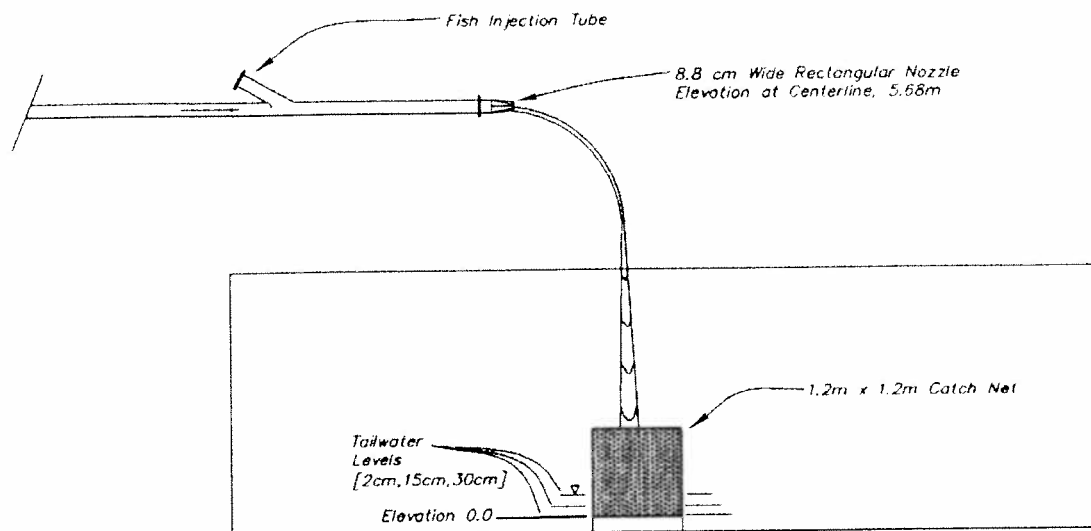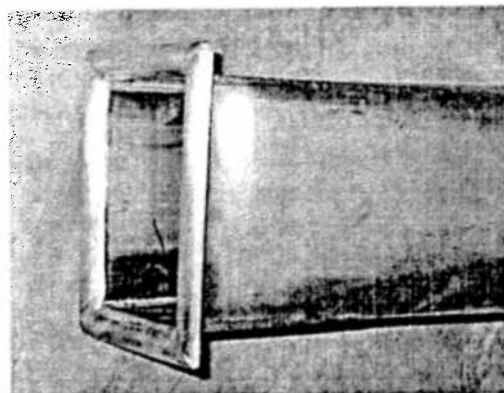Baylar, A., M. E. Emiroglu, and T. Bagatur. 2006. An experimental investigation of aeration performance in stepped spillways. Water and Environment Journal 20 (2006):35-42.

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Fish Injection Tube

8.8 cm Wide Rectangular Nozzle
Elevation at Centerline, 5.68m

1.2m x 1.2m Catch Net

Tailwater
Levels
[2cm,15cm,30cm]

Elevation 0.0

Free-overfall flow nozzle

Free falling spillway jet
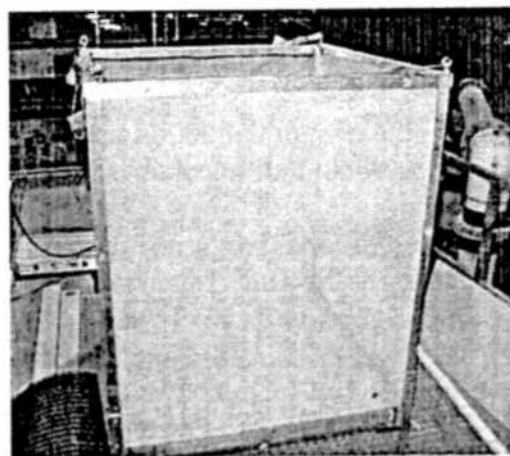
Fish recovery net

Figure 1 -- Weir spillway sectional model test apparatus.

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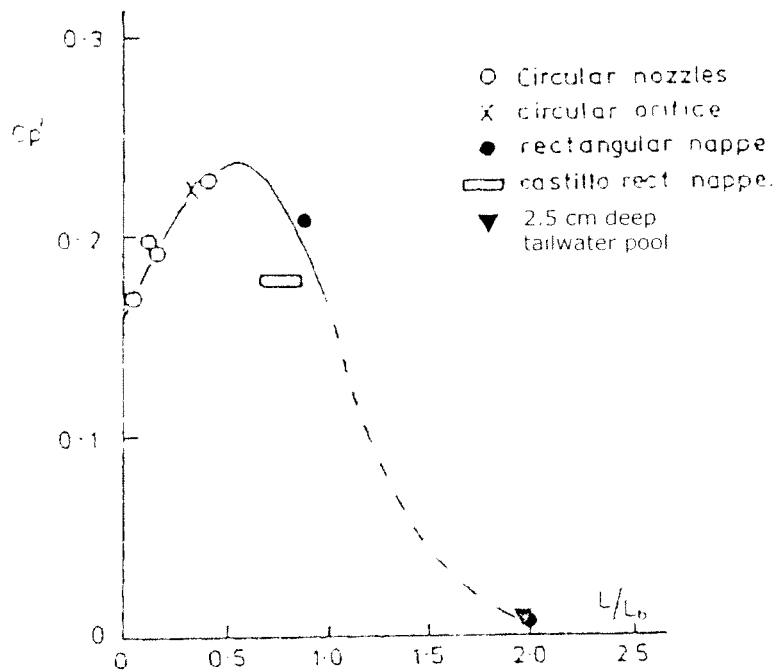
Figure 2 – RMS pressure fluctuation coefficient for 2.5 cm pool depth with jet break-up compared with predicted and experimental data from Ervine et al. (1997).
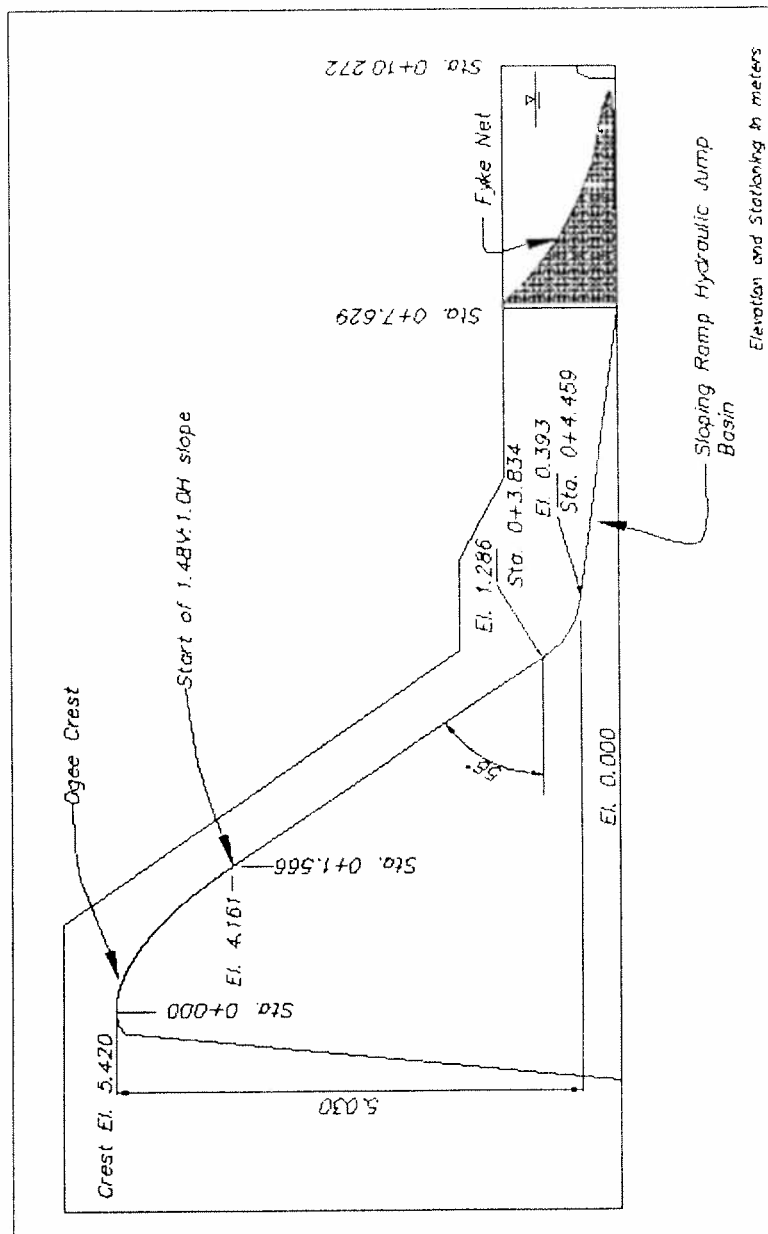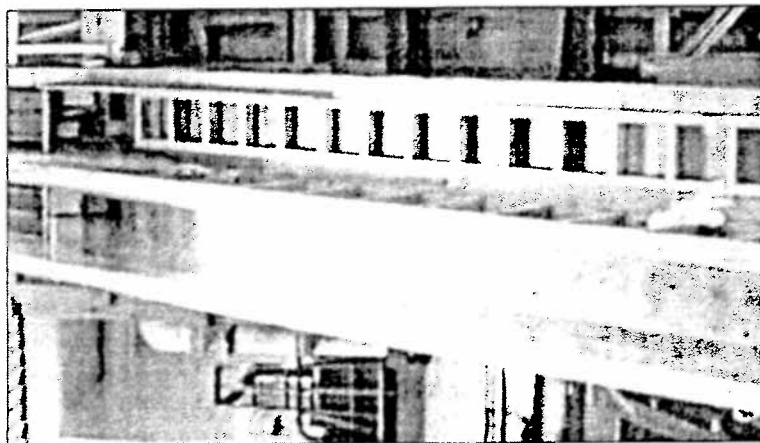
Figure 3 – Smooth ogee spillway sectional model test apparatus.
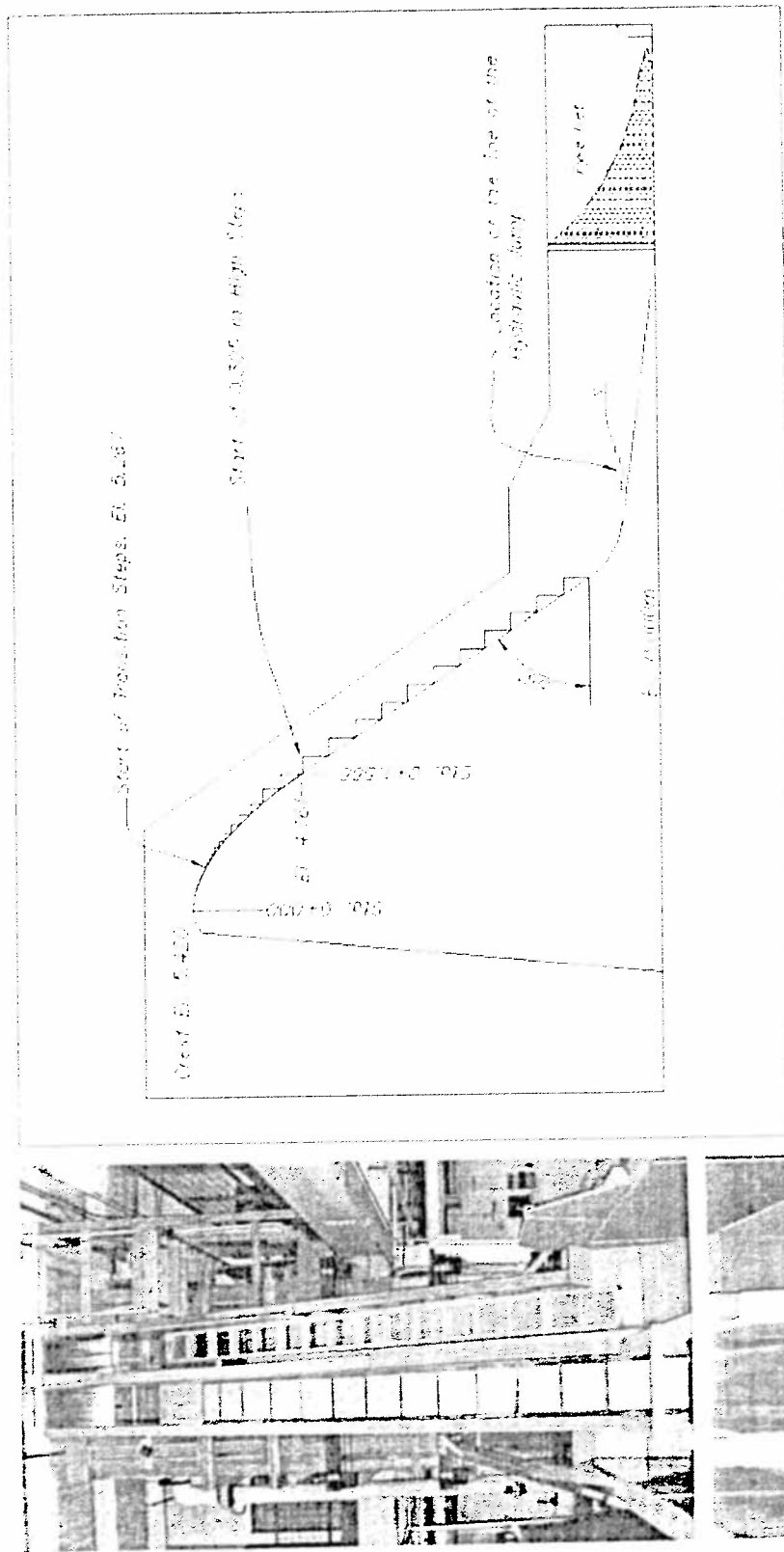
Figure 4 – Stepped ogee spillway sectional model test apparatus.
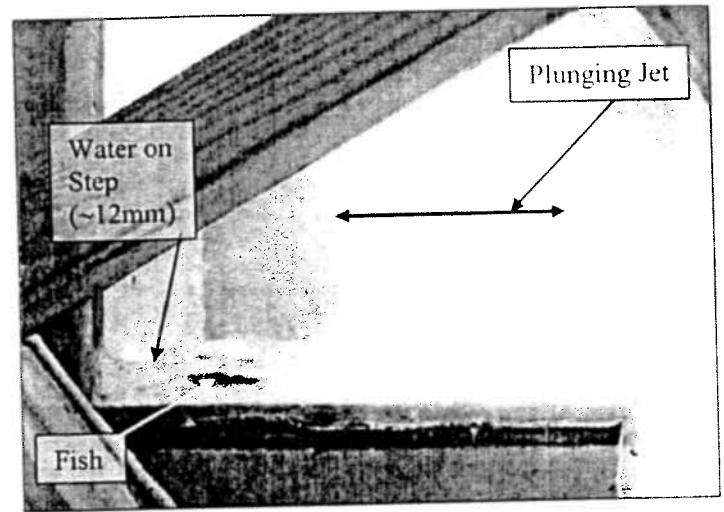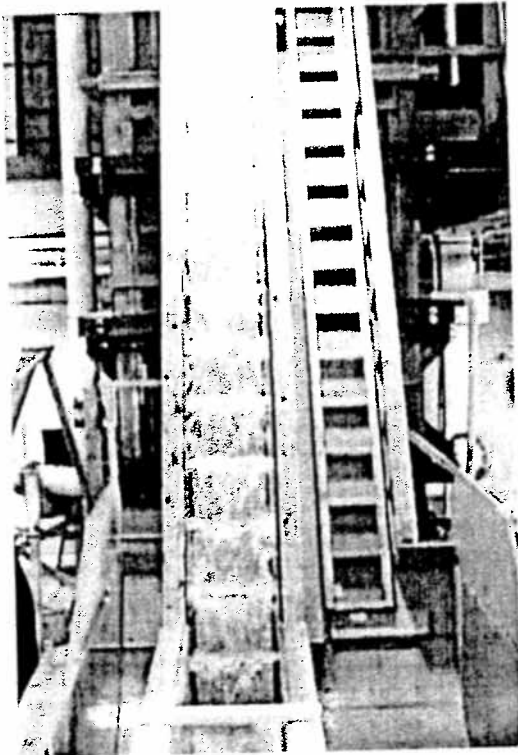
Figure 5 - Nappe flow regime; $Q_u = 0.012 \ m^3/s/m$.
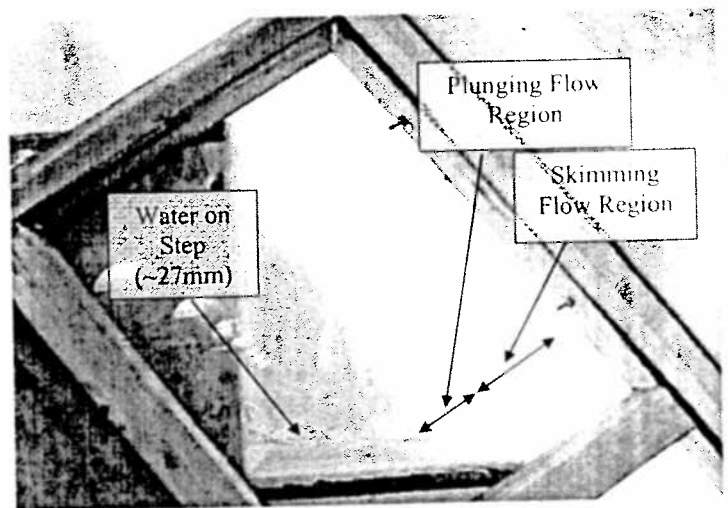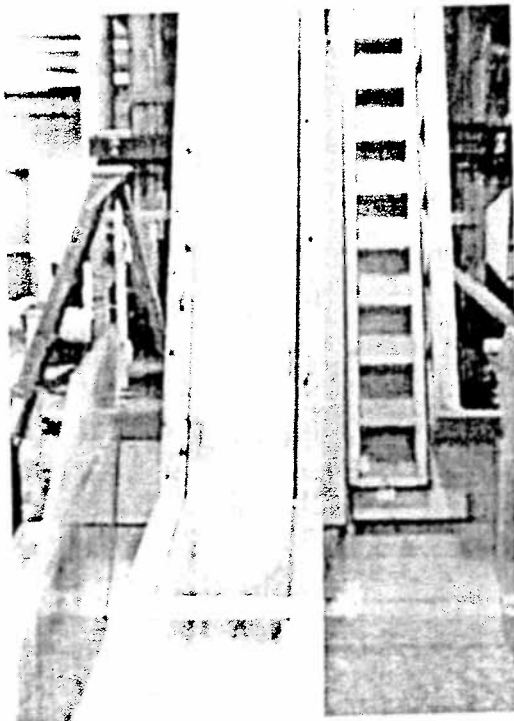
Figure 6 – Transition flow regime, $Q_u = 0.04 \ m^3/s/m$.
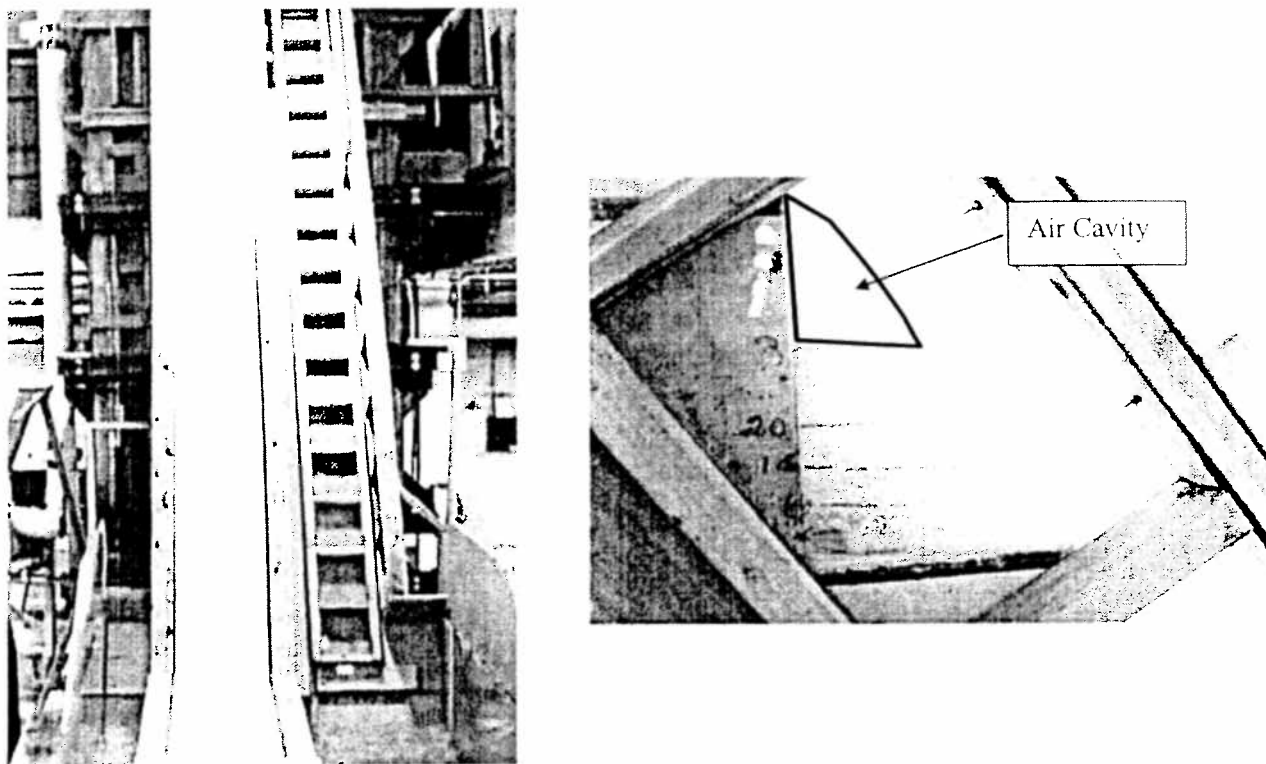
Figure 7 – Maximum test flow, Q_u = 0.24 m³/s/m, upper transition flow regime.
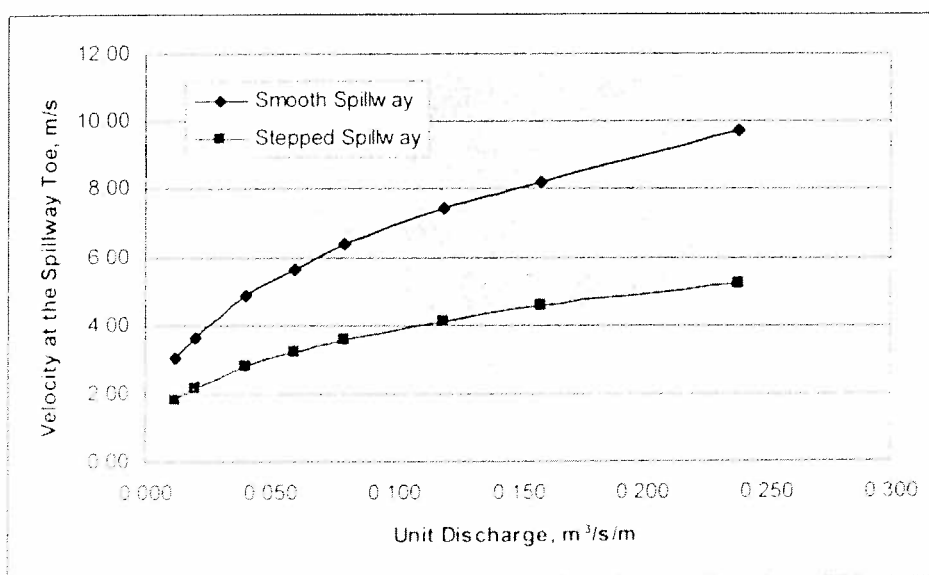
Figure 8 – Spillway toe flow velocity of smooth and stepped spillways as a function of discharge.

Table 1. Survival rates (proportion) and 95% confidence limits (CL) for 25 and 50 mm total length (TL) size classes of fathead minnows, and 25 mm TL hybrid rainbow x cutthroat trout (trout) and razorback suckers released from a 5.7 m high overfall jet spillway structure into a capture net with water depths of 2.5, 15 and 30 cm. Control (C) or treatment (T) fish were released in batches of 10, No. is number of replicates.

Species	TL	Pool Depth (cm)	No.	C or T	Survival	95% CL
fathead minnow	25	2.5 & 15	5	C	1	
	25	2.5	10	T	0.88	0.79 - 0.97
	25	15	10	T	0.97	0.94 - 1.00
	50	30	5	C	1	
	50	2.5	10	T	0.78	0.65 - 0.93
	50	15	10	T	0.98	0.94 - 1.01
	50	30	15	T	0.98	0.94 - 1.01
trout	25	2.5	5	C	0.92	0.86 - 0.98
	25	2.5	15	T	0.94	0.89 - 0.98
	25	15	5	C	0.99	0.95 - 1.02
	25	15	15	T	0.97	0.92 - 1.01
razorback sucker	25	2.5 & 15	5	C	0.98	0.92 - 1.04
	25	2.5	15	T	0.80	0.72 - 0.88
	25	15	5	T	1	0.92 - 1.01

Table 2. Parameter estimates, 95% profile likelihood confidence limits (CL), and significance tests for main effects in a logistic regression model analysis of survival rates as a function of species (fathead minnow (FM), hybrid rainbow x cutthroat trout (TRT), and razorback sucker (RZB)) and pool depth for free-overfall jet spillway experiments. Pool depths were 2.5, 15, and 30 cm.

Parameter	df	Estimate	SE	95% CL	Chi-square	P-value
Intercept	1	4.8049	0.7600	3.4716 to 6.5433	39.97	<0.0001
Species						
FM	1	-1.0515	0.4093	-1.9153 to -0.2911	6.60	0.0102
RZB	1	-1.1892	0.4423	-2.1047 to -0.3491	7.23	0.0072
TRT	0	0				
Pool depth						
2.5	1	-2.1177	0.6742	-3.7288 to -0.9735	9.87	0.0017
15.0	1	-0.2517	0.7431	-1.9490 to 1.0905	0.11	0.7348
30.0	0	0				

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Table 3. Percent mortality, and percent of fish with eye, fin, and integument damage or bruises for small (25 mm total length (TL)) and large (50 mm TL) fathead minnow and small hybrid rainbow x cutthroat trout (trout) from a 5.7 m high overfall jet spillway structure into a capture net with water depths of 2.5, 15 and 30 cm. Control (C) or treatment (T) fish were released in batches.

Species	TL	Depth (cm)	No.	C or T	Mortality	Eye	Fins	Bruise	Integument
fathead minnow	25	2.5	68	C	0.0	0.0	4.4	0.0	0.0
	25	2.5	45	T	0.0	0.0	22.2	4.4	0.0
	25	15	101	T	2.0	0.0	5.0	3.0	0.0
	25	30	50	C	0.0	0.0	2.0	0.0	0.0
	25	30	50	T	0.0	0.0	8.0	2.0	0.0
	50	30	104	C	0.0	0.0	5.8	1.0	1.9
	50	30	95	T	0.0	0.0	10.5	1.1	0.0
trout	25	2.5 & 15	111	C	0.0	0.0	63.5	1.0	0
	25	2.5	50	T	10.0	2.0	76.0	4.0	6.0
	25	15	60	T	0.0	0.0	58.3	1.7	0.0

Table 4. Survival rates (proportion) and 95% confidence limits (CL) for 25 and 50 mm total length (TL) size classes of fathead minnows and hybrid rainbow x cutthroat trout (trout), and 25 mm TL razorback suckers released from a 5.4 m high, smooth-surfaced, ogee-shaped spillway structure at flows of 0.012, 0.02, 0.04, 0.08, 0.16, and 0.24 m³/s/m. Control (C) or treatment (T) fish were released in batches of 10, No. was number of replicates.

Species	TL	Flow (m³/s/m)	No.	C or T	Survival	95% CL
fathead minnow	25	0.012 to 0.24	6	C	0.95	0.87 - 1.03
	25	0.012	3	T	0.97	0.82 - 1.11
	25	0.02	3	T	1	
	25	0.04	3	T	0.97	0.82 - 1.11
	25	0.08	3	T	0.96	0.79 - 1.13
	25	0.16	3	T	0.87	0.72 - 1.01
	25	0.24	2	T	0.90	0
	50	0.012 to 0.24	5	C	1	
	50	0.012	3	T	1	
	50	0.02	2	T	1	
	50	0.04	3	T	1	
	50	0.08	3	T	1	
	50	0.16	3	T	1	
	50	0.24	3	T	0.97	0.82 - 1.11
trout	25	0.012 to 0.24	6	C	0.97	0.91 - 1.02
	25	0.012	3	T	1	
	25	0.02	3	T	0.97	0.82 - 1.11
	25	0.04	3	T	1	
	25	0.08	3	T	1	
	25	0.16	3	T	1	
	25	0.24	3	T	1	
	50	0.012 to 0.24	6	C	1	
	50	0.012	3	T	1	
	50	0.02	3	T	1	
	50	0.04	3	T	1	
	50	0.08	3	T	1	
	50	0.16	3	T	1	
	50	0.24	3	T	1	

razorback sucker	25	0.012 to 0.24	6	C	0.98	0.95 - 1.02
	25	0.012	3	T	1	
	25	0.02	3	T	1	
	25	0.04	3	T	0.97	0.86 - 1.09
	25	0.08	3	T	1	
	25	0.16	3	T	0.97	0.86 - 1.09
	25	0.24	3	T	0.91	0.67 - 1.15

Table 5. Survival rates (proportion) and 95% confidence limits (CL) for 25 and 50 mm total length (TL) size classes of fathead minnows and hybrid rainbow x cutthroat trout (trout), and 25 mm TL razorback suckers released from a 5.4 m high stepped-surface, ogee-shaped spillway structure at flows of 0.012, 0.02, 0.04, 0.08, 0.16, and 0.24 $m^3/s/m$. Control (C) or treatment (T) fish were released in batches of 10, No. is number of replicates.

Species	TL	Flow ($m^3/s/m$)	No.	C or T	Survival	95% CL
fathead minnow	25	0.012 to 0.24	6	C	1	
	25	0.012	3	T	0.97	0.82 - 1.11
	25	0.02	3	T	0.97	0.82 - 1.11
	25	0.04	3	T	0.97	0.82 - 1.11
	25	0.08	3	T	1	
	25	0.16	3	T	1	
	25	0.24	3	T	0.97	0.82 - 1.11
	50	0.012 to 0.24	6	C	1	
	50	0.012	3	T	1	
	50	0.02	3	T	1	
	50	0.04	3	T	1	
	50	0.08	3	T	1	
	50	0.16	3	T	1	
	50	0.24	3	T	0.97	0.94 - 1.03
trout	25	0.012 to 0.24	6	C	1	
	25	0.012	3	T	1	
	25	0.02	3	T	1	
	25	0.04	3	T	0.96	0.81 - 1.12
	25	0.08	3	T	0.97	0.88 - 1.06
	25	0.16	3	T	0.93	0.65 - 1.22
	25	0.24	3	T	1	
	50	0.012 to 0.24	6	C	1	
	50	0.012	3	T	1	
	50	0.02	3	T	1	
	50	0.04	3	T	0.97	0.82 - 1.11
	50	0.08	3	T	1	
	50	0.16	3	T	1	
	50	0.24	6	T	0.99	0.95 - 1.02

		0.012 to				
razorback sucker	25	0.24	6	C	0.90	0.82 - 0.98
	25	0.012	5	T	0.89	0.76 - 1.02
	25	0.02	3	T	0.99	0.95 - 1.03
	25	0.04	3	T	0.93	0.65 - 1.22
	25	0.08	3	T	0.92	0.73 - 1.10
	25	0.16	3	T	0.93	0.61 - 1.24
	25	0.24	3	T	0.81	0.40 - 1.23

Table 6. Type III sums of squares and significance tests for main effects in a logistic regression analysis of survival rates of fathead minnow, hybrid rainbow x cutthroat trout, and razorback sucker in experiments with smooth and stepped spillway models; both full and reduced statistical models are shown. Spillway flow rates were 0.012, 0.02, 0.04, 0.08, 0.16, and 0.24 m^3/s/m; we used small (25 mm total length, TL) and large (50 mm TL) fathead minnows and trout, and small razorback suckers.

Source	df	Chi-square	P-value
Full model			
Species	2	9.03	0.0109
Model	1	2.39	0.1223
Flow rate	1	7.11	0.0077
TL class	1	10.63	0.0011
Reduced model			
Species	2	9.10	0.0106
Flow rate	1	7.12	0.0076
TL class	1	10.46	0.0012

Table 7. Parameter estimates, 95% profile likelihood confidence limits (CL), and significance tests for main effects in a logistic regression model analysis of survival rates as a function of species (fathead minnow (FM), hybrid rainbow x cutthroat trout (TRT), and razorback sucker (RZB)), spillway flow rate (flow), and total length (TL) class (TL 25 = 25 mm TL, 50 = 50 mm TL) in tests with smooth and stepped spillways (non-significant model effect removed). Spillway flow rates were 0.012, 0.02, 0.04, 0.08, 0.16, and 0.24 $m^3/s/m$; we used small (25 mm TL) and large (50 mm TL) fathead minnows and trout, and small razorback suckers.

Parameter	df	Estimate	SE	95% CL	Chi-square	P-value
Intercept	1	6.1667	0.6330	5.0420 to 7.5580	94.91	<0.0001
Species						
FM	1	-0.4903	0.4616	-1.4365 to 0.4026	1.13	0.2882
RZB	1	-1.2198	0.4382	-2.1395 to -0.4004	7.75	0.0054
TRT	0	0				
Flow	1	-0.3867	0.1429	-0.6677 to -0.1043	7.33	0.0068
TL 25	1	-1.6165	0.5641	-2.8742 to -0.6019	8.21	0.0042
TL 50	0	0				

Table 8. Percent mortality, and percent of fish with eye, fin, and integument damage or bruises for small (25 mm total length (TL)) fathead minnow and razorback sucker and large (50 mm TL) hybrid rainbow x cutthroat trout (trout) released from a 5.4 m high smooth-surfaced, ogee-shaped spillway structure at flows of 0.012, 0.08, and 0.24 $m^3/s/m$. Control (C) or treatment (T) fish were released in batches.

Species	TL	Flow ($m^3/s/m$)	No.	C or T	Mortality	Eye	Fins	Bruise	Integument
fathead minnow	25	0.08	103	C	0.0	0.0	9.7	0.0	0.0
	25	0.012	108	T	0.0	0.0	13.9	2.8	0.0
	25	0.08	100	T	0.0	0.0	16.0	0.0	0.0
	25	0.24	100	T	0.0	0.0	12.0	0.0	0.0
trout	50	0.08	103	C	0.0	0.0		3.4	1.7
	50	0.012	108	T	0.0	0.0		4.0	0.0
	50	0.08	100	T	0.0	0.0		2.7	0.0
	50	0.24	100	T	0.0	0.0		2.7	2.7
razorback sucker	25	0.08	104	C	0.0	0.0	13.0	1.0	0.0
	25	0.012	105	T	0.0	0.0	17.0	2.0	0.0
	25	0.08	100	T	0.0	0.0	15.0	0.0	0.0
	25	0.24	102	T	0.0	1.0	14.0	0.0	0.0

Table 9. Percent mortality, and percent of fish with eye, fin, and integument damage or bruises for small (25 mm total length (TL)) fathead minnow, hybrid rainbow x cutthroat trout (trout), and razorback sucker released from a 5.4 m high stepped-surface, ogee-shaped spillway structure at flows of 0.012, 0.08, and 0.24 $m^3/s/m$. Control (C) or treatment (T) fish were released in batches.

Species	TL	Flow $(m^3/s/m)$	No.	C or T	Mortality	Eye	Fins	Bruise	Integument
fathead minnow	25	0.08	99	C	0.0	0.0	5.4	2.1	0.0
	25	0.012	127	T	3.1	2.4	6.3	3.9	0.0
	25	0.08	128	T	1.6	0.8	11.7	3.1	0.0
	25	0.24	105	C	0.0	0.0	7.6	2.9	0.0
	25	0.24	100	T	0.0	0.0	5.0	2.0	0.0
trout	25	0.08	129	C	0.0	0.0	100.0	1.8	3.1
	25	0.012	95	T	0.0	0.0	100.0	4.2	3.2
	25	0.08	90	T	1.1	1.1	100.0	7.8	5.6
	25	0.24	44	T	0.0	0.0	100.0	2.3	2.3
razorback sucker	25	0.08	104	C	0.0	0.0	3.8	1.9	1.0
	25	0.012	105	T	13.3	1.0	4.8	21.9	0.0
	25	0.08	100	T	3.0	0.0	0.0	16.0	0.0
	25	0.24	102	T	0.0	0.0	5.9	8.8	2.0