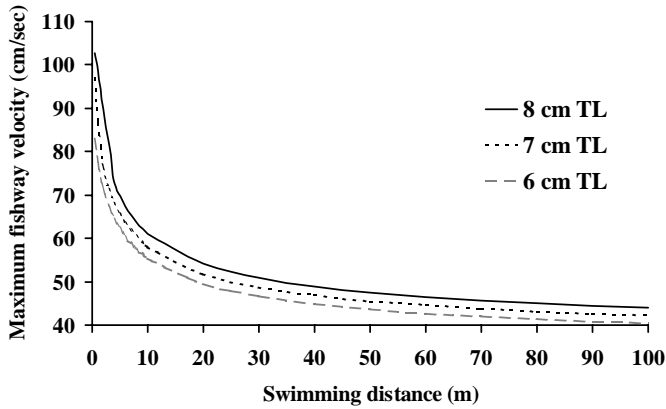
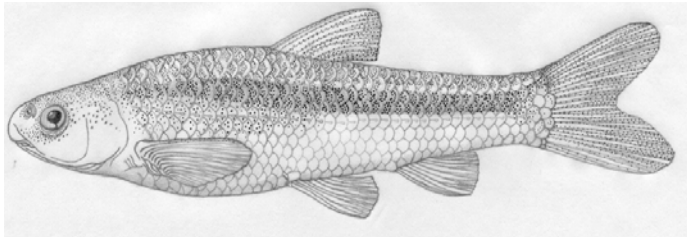
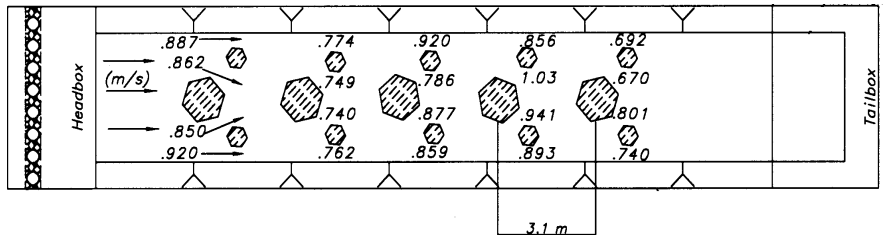


SWIMMING PERFORMANCE OF RIO GRANDE SILVERY MINNOW



Plan view, model of rock channel fishway



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EXECUTIVE SUMMARY

The reach of the Rio Grande, New Mexico that supports remaining endangered Rio Grande silvery minnow *Hybognathus amarus* is dissected by numerous diversion dams that prevent upstream movement of fish. Upstream movement by adult silvery minnows is needed to offset downstream transport of semi-buoyant eggs and larvae following reproduction. Re-establishment of upstream colonization pathways for Rio Grande silvery minnow may require construction of artificial structures (fishways) for fish passage over low-head diversion dams in the middle Rio Grande. To assist with determining optimal passage designs, we assessed aspects of swimming performance and behavior of the Rio Grande silvery minnow in a variety of experimental settings. Results of experiments conducted showed that Rio Grande silvery minnow were capable and motivated swimmers. Rio Grande silvery minnow were capable of swimming at speeds up to 118 cm/sec for short periods of time in a swimming chamber at water temperatures of 15, 19, and 23 C. Swimming endurance increased as water velocity declined; a threshold for an exponential increase in swimming performance was noted at water velocities of 45 to 60 cm/sec. The threshold may represent a transition from anaerobic sprint swimming to more sustained aerobic swimming. Water temperature and fish length were positively correlated with swimming endurance. Rio Grande silvery minnow were also capable of long distance swimming over a relatively short time period; individuals routinely swam a static water distance equivalent of 50 km or more in less than 72 hr. Flume tests revealed that Rio Grande silvery minnow were capable of swimming over a variety of substrate particle sizes in a range of flow velocity conditions. Silvery minnow in the flume used velocity breaks behind cobble particles and the boundary layer to proceed upstream in an energetically efficient manner. We also measured passage rates of Rio Grande silvery minnows in four constructed fishways. We did not observe passage of silvery minnow released into Denil and single vertical slot fishways. High water velocities and complex, turbulent flow fields were the likely reason for passage failure. Up to 50% passage was observed in a dual vertical slot fishway at a relatively low water velocity; passage was only 8% at a higher velocity. Less turbulent flows were a likely reason for higher passage success compared to Denil and single vertical slot fishways. Wild and hatchery fish successfully ascended a rock channel fishway with a 1% hydraulic gradient. About 75% of all fish released passed the rock channel fishway in both low and high velocity flow conditions. Observations with underwater cameras and vertical velocity profiles suggested silvery minnow

used the lower velocity boundary layer and breaks adjacent to high flow zones to swim upstream. The mosaic of water velocities present in the rock channel fishway was likely the reason for relatively high passage success. We integrated time to fatigue relationships with hypothetical passage conditions such as fishway length and flow velocity, water temperature, and fish length, to determine design characteristics for structures. Recommendations made were based on functional swimming relationships and should assist managers tasked with design of structures appropriate for successful passage of Rio Grande silvery minnow. We also discuss uncertainties associated with fish use of the boundary layer, attraction flows, and interpretation of longer distance swimming ability. Because data gathered in this investigation address mostly design considerations related to swimming physiology of silvery minnow, the ultimate decision to construct a fishway should be based on a compendium of other supporting information.

INTRODUCTION

Rio Grande silvery minnow is endemic to the Rio Grande Basin and formerly widespread and abundant in warm water main stem reaches and larger tributaries (Pflieger 1980, Bestgen et al. 1989, Bestgen and Platania 1990, Bestgen and Platania 1991, Platania 1991). Rio Grande silvery minnow presently occurs only in the middle Rio Grande, New Mexico, a small percentage of its former range. As a result of reductions in historical range and threats to remaining populations, the species is presently listed as endangered by the U. S. Fish and Wildlife Service (U. S. Department of the Interior 1994).

Factors implicated in the demise of Rio Grande silvery minnow include habitat modifications, hybridization, altered flow regimes, negative effects of non-indigenous fishes, and disruption of dispersal routes (Bestgen et al. 1989, Bestgen and Platania 1990, Bestgen and Platania 1991, Platania 1991, Cook et al. 1992, Bestgen and Propst 1996, Platania and Altenbach 1998). The importance of maintaining dispersal routes for plains stream fishes was hypothesized by Cross et al. (1985) and circumstantial evidence of negative effects of dams on upstream movement has been presented elsewhere (Cross et al. 1985, Bestgen and Platania 1990, Bestgen and Platania 1991, Platania 1991, Winston et al. 1991, Fausch and Bestgen 1997, Platania and Altenbach 1998, Luttrell et al. 1999). Unobstructed dispersal routes are likely important for several endemic plains stream species including Rio Grande silvery minnow because they produce semi-buoyant eggs and larvae that drift long distances downstream (Moore 1944, Cross et al. 1985, Fausch and Bestgen 1997, Platania and Altenbach 1998). A consequence of downstream dispersal of early life stages is that juveniles and adults likely need to re-colonize upstream reaches for populations to persist.

Timing of upstream dispersal of Rio Grande silvery minnow, the life stages involved, and environmental conditions under which movements occur are not well understood. Large concentrations of Rio Grande silvery minnow and other Rio Grande fishes have been found downstream of diversion dams in late summer and fall indicating that re-colonization of upstream reaches may occur at those times (Koster 1957, Bestgen and Platania 1991), although concentrations may also have resulted from individuals moving upstream to escape dessication of downstream reaches. Upstream movements of plains minnow *Hybognathus placitus* in the South Canadian River, New Mexico, were observed in spring which may have been in response to onset of the reproductive season (Fausch and Bestgen 1997). Regardless of the timing and

extent of movements, re-colonization pathways may be essential for long-term persistence of Rio Grande silvery minnow in the middle Rio Grande, New Mexico.

Re-establishment of upstream colonization pathways for Rio Grande silvery minnow may require construction of artificial structures (fishways) for fish passage over low-head diversion dams in the middle Rio Grande. Fishways have been used extensively in the Pacific Northwest region of the United States and western Canada to allow for upstream passage of salmon migrating back to spawning areas. Traditional fishways were engineered primarily for relatively large-bodied salmonids that are powerful swimmers. Unfortunately, few fishways have been designed for species indigenous to low gradient streams like the Rio Grande. Even less is known about passage characteristics of plains stream fishes that are relatively small-bodied (100 mm total length (TL) or less) and whose swimming physiology is poorly understood. Existing theory suggests that swimming performance characteristics of fish vary by taxon and body-size characteristics (Beamish 1978). Other factors that may affect swimming and passage performance include water turbulence.

We assessed aspects of swimming performance and behavior of the Rio Grande silvery minnow in a variety of experimental settings. First, we measured swimming endurance (time to fatigue) of silvery minnow in a swimming chamber at water velocities up to 120 cm/sec in water temperatures of 15, 19, and 23 C. Second, we measured long-distance swimming ability of silvery minnow in those same temperature regimes. Third, we estimated the proportion and passage rate of silvery minnow that swam the length of a flume with differing water velocities and substrate particle sizes. Finally, we determined the proportion and passage rate of silvery minnow that swam the length of a Denil, single vertical slot, dual vertical slot, and rock channel fishway. We then used swimming performance data to evaluate tradeoffs between silvery minnow swimming endurance and different combinations of fishway channel length and velocity. Understanding laboratory swimming performance and behavior may assist managers tasked with design of fishways capable of passing Rio Grande silvery minnow in natural rivers.

METHODS

Swimming performance of Rio Grande silvery minnow was investigated in three integrated studies. The first study was designed to assess shorter duration (220 min or less) swimming performance of Rio Grande silvery minnow in a swim chamber, a flume, and in a baffled Denil-type fishway. The second study progressed from existing swim chamber information and was designed to assess longer duration (220 to 4320 min) swimming performance of silvery minnow. The third portion of the study was to conduct tests of passage rates of silvery minnow in single and dual vertical slot fishways, and a rock channel fishway. With just a few exceptions, wild Rio Grande silvery minnows were used in tests of fish endurance and passage.

Fish culture and handling.—Wild Rio Grande silvery minnow adults age-1 or older (mean total length (TL) = 71 mm, range 55 to 88 mm) were obtained from the main stem Rio Grande in central New Mexico (S. P. Platania, University of New Mexico, pers. comm.). Wild fish were preferred over cultured stocks because of possible differences in swimming capabilities. Fish were shipped in batches of less than 100 animals via airfreight to the Aquatic Resources Laboratory at Colorado State University. Testing began on 31 Oct 2001. Lack of wild fish of appropriate size and low water conditions in New Mexico in 2002 necessitated use of a few cultured fish to finish tests; those were 80 to 90 mm TL.

Separate batches of fish were quarantined upon arrival in 900 l circular tanks. Water was from a well source delivered at 18.5 C and was allowed to flow-through tanks at an exchange rate of greater than twice per hour. Aeration was achieved with an air stone. Water velocity in tanks was maintained at 10 cm/sec to exercise fish and photoperiod was 14 hours light and 10 dark. Tanks were mostly covered with black plastic to avoid disturbance and reduce stress. Fish were trained to feed on a prepared diet of frozen brine shrimp that was offered several times each day. As they accepted brine shrimp, Tetra-min tropical flake food was introduced. Because silvery minnow preferred brine shrimp, that food likely made up a majority of their diet.

Prior to conducting swim chamber tests, small groups of healthy fish were temperature acclimated in a separate tank for 4 days or more prior to testing and were fed normally. Individuals to be tested were held in a separate acclimation tank and not fed for 24 hr (Beamish 1978). A range of water velocities was made available to fish in the acclimation tanks and these tanks were also enclosed in black plastic to minimize disturbance. For tests conducted at 19 C,

water was flow-through in acclimation tanks. In acclimation tanks that held fish for tests conducted at 15 and 23 C, a small quantity of water was re-circulated but exchange rates exceeded 15 times per day.

Because wild Rio Grande silvery minnows are often disease-prone in captivity (pers. comm, C. Altenbach, Albuquerque Aquarium, J. Landye, U. S. Fish and Wildlife Service), prophylactic drug treatments were used to keep fish healthy. Treatments were administered immediately after capture of fish from the wild and as needed afterward. Fish testing was suspended when one or more fish showed symptoms of disease. The most common pathogen was determined to be *Flavobacterium columnaris* (pers. comm, Dr. Peter Walker, fish pathologist, Colorado Division of Wildlife). Symptoms include disorientation, organ failure (mostly liver), redness and swelling inside the cranium or on the snout, and fin erosion. This bacterial strain was apparently very proteolytic. Isolated silvery minnows that succumbed were found with little tissue remaining on the head within just a few hours after death. Treatments included nitrofurazone (10 mg/l), terramycin introduced into the diet as well as intraperitoneally by injection (1 mg/18 g of fish), and a 10 mg/l oxolinic acid bath for 24 hours. Stress reduction was effected by minimizing handling, frequent feedings, high water exchange rates, and keeping moderate densities of fish in circular tanks (not troughs) that were allowed to accumulate biofilms. Stress reduction tactics seemed as important to maintaining healthy fish as prophylactic treatments. Wild fish received in January were more prone to *F. columnaris* than were fish received in shipments in November or April.

Relatively late in the study, we were unable to obtain wild Rio Grande silvery minnows of sufficient size to finish testing so a few hatchery fish were used. These were used only to supplement longer-distance swimming tests at 15 C, and to complete testing in dual vertical slot and rock channel fishways. Use of hatchery fish is noted so comparisons can be made.

Swim chamber description and testing.— The swim chamber was constructed with 7.6 cm inside diameter, schedule 40, clear PVC pipe (Fig. 1). That diameter of pipe was chosen to ensure that maximum fish cross-sectional area was less than 10% of swim chamber area (Bell and Terhune 1970), which minimizes blocking effects (Smit et al. 1971). The apparatus was composed of two 1.25 m sections of pipe joined by a union. The open-ended upper section received inflow tubes from each of three water pumps that were used singly or together to achieve desired velocities. Pumps were submerged with the entire swim chamber apparatus in a 3.05-m-long trough filled with well water. Speed of each pump was controlled with a rheostat.

Pump inflow tubes placed in the open end of the larger PVC pipe created a venturi effect, which achieved higher velocities with less turbulence than if the pumps were directly linked to the chamber in a closed system. The lower 1.25 m section of pipe was the actual swimming chamber, where fish were confined with a plastic-coated large mesh screen on each end. Dye and neutrally buoyant gelatinous beads pumped through the system showed that as water flowed through the upper section of the apparatus and the upper screen, flow turbulence in the swim chamber was reduced and an even velocity distribution was achieved. A GF Signet flow meter mounted on the upper section of the apparatus was used to obtain first estimates of water velocity. Passage rate of five beads were timed through a 1 m section of the swimming chamber prior to each test and were averaged to obtain final estimates of test velocities. The removable union and screen at the lower end of the swim chamber facilitated introduction and retrieval of test fish. A 30-cm section in the middle of the swimming chamber was covered with black plastic which provided cover and visual orientation for fish. The dark area was generally attractive to fish which prevented most individuals from moving to the upper screen where velocity was slightly reduced. When fish did move to the upper screen they were encouraged to retreat to the plastic enclosure area by the presence of bright lights or short bursts of higher velocity water. We used an electrified barrier (Ward et al. 2002) for a few long-distance swimming tests late in the study; fish avoided the barrier but did not appear to be adversely affected by it. A small light source was provided when fish swam at night which aided orientation. Temperature was regulated with an external water reservoir and the swim chamber and the reservoir were aerated.

Three different types of swimming chamber performance tests were completed with Rio Grande silvery minnow. We first conducted critical swimming speed experiments which were adapted from Brett (1964). Fasted fish were randomly selected and allowed either a relatively long (mean about 14 hr, N = 6) or short (about 2 hr, N = 6) acclimation period in the swim chamber. Velocity was set at about 10 cm/sec to orient fish; flow also provided freshly aerated water at 19 C. After acclimation, water velocity was increased by 10 cm/sec every 20 min until the fish could not maintain in the current and was swept to the lower screen. When the fish failed the time was noted for use in estimation of critical swimming speed. The fish was removed, checked for injuries, weighed (g) and measured (total length, TL in mm), and placed in a recovery tank. Fish were not used more than once. Critical swimming speed (U_{crit}) was then determined by the formula from Beamish (1978):

$$U_{\text{crit}} = u_i + (t_i/t_{ii} * u_{ii}),$$

where u_i is the highest velocity (cm/sec) maintained for the entire prescribed period of 20 min, u_{ii} is the velocity increment (usually 10 cm/sec), t_i is the time (min) that the fish swam before it fatigued in the final time interval, and t_{ii} is the duration of the interval (here 20 min).

After we had estimated U_{crit} for 12 individuals, we re-evaluated what the test data were providing. The U_{crit} estimate has a strong historical basis in the literature (Beamish 1978), tests could be conducted in a relatively short time, and estimates likely have a relationship with maximum swimming speeds. However, even the maximum swimming speed parameter may be confounded by fatigue that may occur in the time intervals prior to achieving maximum swimming velocity. The U_{crit} estimate also offered little in the way of understanding the endurance (time to fatigue) of Rio Grande silvery minnow at a given velocity, information which seemed important for defining realistic criteria for passage design.

Therefore, we tested fish at a range of velocities that would permit estimation of a relationship that described endurance as a function of water velocity and would also permit classification into traditional sustained, prolonged, and burst swimming speed categories (Beamish 1978) if such existed for silvery minnow. We chose test velocities at intervals within the extremes of about 25 to 120 cm/sec. Fish were assumed able to swim indefinitely at velocities less than 25 cm/sec. After the acclimation period, we increased water velocity to the desired test speed over about a 2 min interval. Initially, we set the maximum test time at 220 min, after which testing for that fish was terminated.

Finally, additional tests were conducted to determine how long Rio Grande silvery minnow could swim at a sustained cruising pace. Previous tests suggested fish could likely swim long distance at velocities in the 35 to 50 cm/sec range. Therefore, we allowed fish to swim at a set velocity of about 40 cm/sec from 220 min up to 72 hours. Those data allowed us to determine distance swam, and added to data that described the relationship between swimming duration and current velocity. Comparison of U_{crit} data where fish had short or long acclimation times suggested no difference in performance so all fish were allowed a short, 1 hr acclimation period. We conducted both short and longer-term swimming chamber tests at temperatures of 15, 19, or 23 C to estimate effects on swimming performance. This range of temperatures was thought to approximate conditions present in the Rio Grande, New Mexico, in spring and autumn, and portions of the summer and winter (KRB, pers. obs).

For all tests, a fish was considered to have failed when it impinged on the screen and could not be encouraged to swim by gentle probing with a glass rod, a response to a bright light, or with short bursts of high velocity water. A fish was also considered to “fail” when the same stimuli could not prevent the test animal from occupying the area just downstream of the screen on the upstream end of the swimming chamber, where velocities were somewhat reduced. During high velocity swimming tests, some fish would impinge, perhaps due to a fright response, before fatigue was reached. Water velocity was then reduced and the fish was allowed to reposition itself in the swimming chamber (Smit et al. 1971). Water velocity was then increased to nominal again. If the fish failed immediately, the first failure was determined genuine and that swimming endurance duration was recorded. If the fish continued swimming, the time of the first and second intervals was summed to obtain an estimate of swimming endurance. Fish that never swam were recorded as non-swimmers. Fish were then removed, checked for injuries, weighed (nearest 0.1 g), and measured (TL). Fish were placed in a recovery tank and not tested again.

Flume studies.—Volitional swimming performance of silvery minnow over different substrate particle sizes was assessed in a plexiglass flume 18.3 m long, and 0.91 m-wide (Fig. 2). Removable panels on the bottom of the flume allowed for tests with coarse-sand (1 mm diameter), gravel (25 mm), and cobble (152 mm) substrate. Flume slope was set horizontal (zero gradient) for tests. Water was 30.5 cm deep and water velocities used in tests with each substrate particle size were 8, 23, 38, and 53 cm/sec. Water velocities were manipulated by changing pump speed and the number of tailboards in the downstream end of the flume. Vertical water velocity profiles for each of the velocity and substrate combinations were also measured (Figs. 3 - 5). The vertical water velocity profiles were intended to show the relative distribution of water velocities in the channel at the approximate target velocities. Mean water column velocity at 15 cm above the bed was measured and adjusted to target conditions prior to each test.

Upstream and downstream ends of a portion of the flume were screened with perforated steel plate (upstream) or nylon netting (downstream) so that fish could not escape. This reduced the effective length of the flume to 14.6 m for sand and cobble substrate, and 12.2 m for the gravel; the latter was shorter in the absence of one gravel panel. Fish were held in an enclosure at the downstream end of the flume at the channel margin and allowed to orient to the current for 1-10 min prior to testing. One or two fish were released at a time and the upstream swimming progress of each individual was measured at intervals of 1, 2, 3, 4, 5, 10, and 15 min.

Observations through the clear plexiglass walls were made at a distance so that fish were not disturbed. Each fish was treated as an independent observation because individuals had few observable effects on each other. Time to swim the flume length was recorded if a fish finished. For fish that did not finish after 15 min, maximum upstream swimming distance was recorded. We also made observations of fish swimming behavior, vertical position, and use of substrate particles in each of the flow and substrate combinations.

Fishway studies.— Four prototype-size fishways were constructed in the laboratory to evaluate silvery minnow passage response. Denil, vertical slot, and dual vertical slot fishways and a rock channel fishway with boulder weirs were tested. Due to limited availability of test fish, we focused testing on the most promising fishways and hydraulic conditions. All fishway tests were based on volitional passage. For all fishway tests, groups of 5 to 15 fish were released into the tailwater downstream of the fishway. Flow and tailwater depth were adjusted prior to tests to establish desired fishway- and attraction-flow conditions. The constructed channel slope of each fishway was not changed during testing. The number of fish that passed through the fishway, their swimming times, and when possible, behavioral observations were recorded. We were not able to immediately capture fish that exited the fishways without disturbing the progress of other fish in the model. In a few instances, fish that had passed were observed retreating from the headbox back to the fishway. Therefore, for all fishways except the rock channel we recorded the total number of finishes, recognizing that a single fish may have sometimes finished more than once.

Denil fishway.—The Denil fishway is heavily baffled to dissipate flow energy by rapid generation of vertical turbulence. Denil fishways are typically set at slopes of 10 (0.1m/m) to 20 (0.2 m/m) percent. Closely-spaced flow baffles with center passages are canted upstream at a 45^B to the channel floor (Fig. 6). The Denil design requires that fish pass by swimming the length of the chute in a single burst. For long fishways, resting areas between multiple baffled runs are used. Flow is maintained in a nearly constant mid-channel velocity profile along the fishway length. In profile, a shallow low-velocity zone exists near the bottom of the baffle opening followed by a nearly continuous increase in velocity toward the water surface. Rajaratnam et al. (1984) found the thickness of the low-velocity zone decreases with increasing discharge. Under proper flow conditions, the low-velocity zone is generally thought the passage path for weak-swimming fishes. Prototype studies of two Denil ladders on the Fairford River, Manitoba and Cowan Lake, Saskatchewan (Katopodis et al.1991) found they provided effective passage for

relatively large-bodied adult sauger *Stizostedion canadense*, walleye *S. vitreum*, white sucker *Catostomus commersoni*, and other resident fish species. These fishways had a 12% slope (0.12 m/m) with run lengths of 5 to 10 m for a total elevation drop of about 2.1 m. Velocities in the weir chutes varied from about 0.7 m/s at 0.2 depth above the bottom to 1.4 m/s at 0.6 depth above the bottom.

The Denil fishway constructed for silvery minnow tests was 1.2 m wide by 7.1 m long with a channel slope of 10 percent (0.1 m/m). The baffles were of standard design (Clay 1995), except the ratio of channel width (B) to baffle clear opening width (b) was increased from the standard 1.7 up to 2.0 to accommodate use of an existing flume. Rajaratnam and Katopodis (1984) found a B/b ratio of 2.0 yielded negligible differences in fishway hydraulic performance compared to the standard design. The fishway approach channel extended 3.2 m downstream of the first Denil baffle. Tests were conducted for a 20 hr period with 113 l/s flow in the fishway and normal tailwater. Flow depth in the fishway measured above the baffle apex was 0.57 m, a flow depth (d) to b ratio of 0.59. Ratio's of d/b less than 1.1 are referred to as small by Katopodis et al. (1997). For flow conditions yielding small d/b ratios, Katopodis found the velocity profile above the baffle apex can be expressed as:

$$u / u'_m = 0.55 + 1.4(y / d)^4 \quad (1)$$

where, u = average velocity at depth y
 u'_m = velocity at $0.75 d$
 d = flow depth

During Denil fishway tests, flow velocity was measured on each baffle 9 cm (y) above the baffle apex. The average velocity measured was 33 cm/s (u). Applying equation 1 to test conditions, predicts a flow velocity of 60 cm/s at $0.75d$ and 117 cm/s at the water surface.

Vertical slot fishway.- A vertical slot fishway uses a series of baffles with vertical slots on the lateral margin of each baffle. Baffles were designed to create lower velocity backwater pools between baffles and higher velocity flow through the baffle slots. The vertical slots allow passage at nearly all depths within the water column and can operate over a relatively large range of flows and river stage. A vertical slot fishway with single slot baffles based on Katopodis' design #2 (Katopodis 1992) were constructed in a 1.7-m-wide and deep and 9-m-long flume (Fig. 7). A false bottom was constructed in the flume at a 5 percent slope (0.05 m/m) for a horizontal distance of 7.31 m. Baffles were spaced at 1.82 m intervals along the slope. Tests were

conducted with a fishway flow of 90 l/s and normal tailwater depth (48 cm). The fishway geometry resulted in a water surface drop of about 9.1 cm across each baffle with an average velocity through the vertical slots of about 1.3 m/s. Velocities between the baffles were lower. The single test was for 21 hr.

Dual vertical slot fishway.- In 1995, Reclamation working with U. S. Fish and Wildlife Service, investigated fishway designs for improving upstream passage of weak swimming cui-ui *Chasmistes cujus* found in Pyramid Lake, Nevada. A number of ladder baffle designs and gradients were studied using laboratory models and numerical simulations. An important objective for the project was design of baffles that maximized the downstream flow within pools between baffles. Field observations of cui-ui attempting to pass through a weir and orifice fishway suggested cui-ui became disoriented by the complex flow field between baffles. Research resulted in a unique dual vertical slot baffle design that produced less pronounced eddy patterns and greater downstream flow alignment between baffles (Fig. 8). The dual vertical slot fishway we tested had a slope and length similar to that for the single vertical slot fishway. Dual-slot baffles have a 30 degree from perpendicular V-shape with the leading edge pointed into the current. On the downstream side, baffle walls form a smooth divergence that guide fish to the baffle slots. Tests were conducted with a fishway flow of 140 l/s and two tailwater depths each greater than normal fishway depth (35.2 cm) for the flow. Tests with high tailwater submergence were conducted to reduce passage velocities to less than 100 cm/s (based on observations of fish performance during the single vertical slot tests), about the lowest practical level. Tailwater depths of 67 cm (78 cm/sec through slot velocity and 1.7 % (0.017 m/m) average hydraulic gradient) and 55 cm (87 cm/sec through slot velocity and 2.1 % (0.021 m/m) average hydraulic gradient) were tested. Test duration was 1 - 2 hr; longer tests were not warranted because most fish that finished did so in a relatively short time.

Rock channel fishway.-Rock fishways are either constructed channels that bypass a portion of river flow around a dam or an in-river rock ramp that provides a low gradient path over a dam. Rock fishways are often chosen because they provide a mosaic of low to high-velocity flow conditions across the channel, conditions thought important to provide opportunity for multi-species passage in several rivers (Table 1). Rock channel fishways may be designed as simple prismatic channels of constant bed slope or may include features such as meanders, pools and riffles, or boulder weirs. As in a natural stream, fishway flow velocity is controlled by stream gradient, bed roughness, channel hydraulic radius, and large-scale flow obstructions.

The experimental rock channel fishway we used was 30 m-long, had a trapezoidal cross-section 2.4 m wide at the bottom, and 2:1 side slopes that were 76 cm deep (Figs. 9, 10, and 11). The upstream 22.8 meters had a channel gradient of about 2% (0.02 m/m) followed by a horizontal downstream section of reduced flow velocity. Overall, hydraulic gradient was 1%. The rock-lining consisted of angular riprap with a D_{50} of 15 cm and a D_{100} of 25 cm. Boulder weirs were formed by placing three, 60 to 90 cm diameter boulders set in a upstream pointing V-shape. The largest boulder was placed in the center of the channel with smaller boulders set back at 30 degrees to perpendicular. Boulders were set apart with a 30 cm clear space. Boulder weirs were spaced at about 3.1 m on center the length of the fishway. Fishway studies were conducted with a flow of 240 l/s. High (average hydraulic gradient = 1.0 % (0.01m/m), pool depths . 22 cm) and low (average hydraulic gradient = 0.5 % (0.005 m/m), pool depths . 26 cm) water velocity tests in the rock fishway were conducted by adjusting fishway entrance depth with model tailboards. Mid-column flow velocity between the boulder weirs in low flow tests ranged from 50 to 75 cm/sec, and was about 75 to 100 cm/sec in high flow tests. In low flow tests, fish were released into the downstream pool created by the tailboards, which allowed for orientation. In the first few high velocity tests (no pool condition), fish were released directly into the current because there was no catchment pool. Lack of orientation time resulted in impingement of a few individuals so the tailrace was modified to create a holding pool for additional high velocity tests. Batches of 10 or 15 individuals were used in all tests.

Because observations of small-bodied Rio Grande silvery minnows were not possible in the rock model fishway, we constantly monitored the number of fish that ascended the model and remained in the upstream headbox for the first two to four hours after fish release. Passage times were also recorded as fish entered the headbox. Thereafter, observations were at irregular intervals, usually during a 24-hr period, but sometimes for as long as 120 hr. Observations were also made at night (about 2300 hrs) the day of release to determine the extent of nocturnal fish movement. Fish were first removed from the headbox only after the initial 2 to 4 hr observation period so that other fish in the model that were close to finishing were not disturbed. During that time period, some fish were observed swimming back into the model so those were not necessarily counted as finishers. Total number of fish that finished was calculated as the number of fish removed plus the maximum number of fish observed in the headbox after those removals. Thus, the total number of fish estimated to finish was conservative, because a fish that finished and never re-entered the headbox to be caught or observed was not counted.

Data analysis.—Swim chamber data were plotted as swimming endurance (min) as a function of water velocity; body lengths per second swum was also reported for critical swimming velocity tests. General relationships for swimming endurance as a function of time for each temperature were fit with non-linear regression, after endurance data were log-log transformed (as $\ln(\ln(\text{min swimming endurance} + 1)) + 1$). We subtracted a velocity constant of 25 cm/s in the non-linear analysis to achieve a better fit for the intercept. This was justified because fish could swim for long periods at low water velocities such that an intercept may never be achieved; subtracting the constant had no effect of slope estimates. We also fit a response surface regression to model swimming endurance (response variable data again as $\ln(\ln(\text{min swimming endurance} + 1)) + 1$) as a joint function of water velocity, temperature, their squared and interaction terms, and fish TL. This relationship may be useful for predicting fish swimming performance at various flow and temperature combinations that we did not test directly. We initially estimated effects of water temperature on short-term swimming performance with analysis of covariance (ANCOVA). However, the improved fit of the double-logged response data negated the need for these relationships so they were eliminated. We also used velocity as a weight in non-linear and response surface regressions so that model fits at the more critical higher velocities were enhanced.

Flume response data were proportion of fish (finish = success, failure to finish = failure) that swam the entire flume length in the test period and duration of successful swimming trials. Each fish was treated as an independent observation. Fish success/failure data were treated as a binary response in a logistic regression model that estimated the probability that a fish would swim the flume length. Swim duration data were analyzed as a continuous variable and were not transformed. Each of these response data were analyzed as a function of current velocity (as a surrogate for gradient) and substrate particle size in a response surface regression. Although substrate particle size and water velocity could just as easily be considered class variables, they were used as continuous ones here because fish appeared to respond to particle size and velocity gradients in a regular and predictable manner. This analysis was also compact and allowed for estimation of functional relationships, which seemed more useful than presentation of multiple hypothesis tests with their attendant difficulties (Yoccoz 1991). We also interpreted differences in flume swimming performance among the different combinations of velocity and substrate particle size in light of behavioral observations made during tests.

Performance data for Denil, single and dual vertical slot, and rock model fishways were presented as the proportion of fish tested that successfully ascended each fishway under each set of experimental conditions. Mean finish times, proportion of fish that finished in day versus night, effects of low and high flows, with and without a holding pool, and effect of wild versus hatchery fish on those responses were also reported for the rock channel fishway.

RESULTS

Swim chamber tests, critical swimming speed estimates.— Performance of Rio Grande silvery minnow with short and long acclimation times, estimated by critical swimming speed and number of body lengths swam/sec, were similar (Fig. 12, Table 2). The overall mean U_{crit} was 51.5 cm/sec which translated into an average swimming rate of 7.8 body lengths/sec. Regressions showed positive slopes for relationships that described U_{crit} and swimming rate as a function of fish TL. This suggested that larger fish were capable of faster swimming speeds and rates than smaller fish.

Swim chamber tests, endurance swimming.— Non-linear regression relationships of swimming endurance as a function of water velocity suggested an exponential decline in swimming endurance of Rio Grande silvery minnow as water velocity increased (Fig. 13, Table 3). At all temperatures, Rio Grande silvery minnows were capable of swimming at a water velocity of 100 to 120 cm/sec for 5-15 seconds. Swimming endurance increased in a generally linear fashion as velocity declined from > 100 cm/sec to about 60 cm/sec. Swimming endurance increased exponentially as water velocity declined below 50 cm/sec to about 25 cm/sec, the lowest level tested. The single threshold we noted for increased swimming endurance at all temperatures appeared to be when water velocities were in the range of 45 to 60 cm/sec. It should be noted that most fish in tests 4- to 72-hours long with water velocities of 35 to 50 cm/sec were still swimming when the test was terminated. Thus, reported endurance at water velocities < 50 cm/sec were perhaps conservative.

We attempted to test fish swimming endurance along a continuum of water velocities but found a regular gap in performance data at swimming velocities less than about 60 cm/sec and between endurance times of about 15 to 220 min because there were few failures. This was due to the threshold effect in which fish could swim much longer at those lower velocities, so points along the entire continuum were difficult to obtain.

At a given water velocity, regression relationship predictions showed that Rio Grande silvery minnow were capable of swimming longer durations as water temperature increased, particularly at higher water velocities (Fig. 14). This was evident from the smaller slopes and intercepts for the non-linear regression relationships as water temperature increased. For example, at an intermediate velocity of 50 cm/sec, non-linear regression predictions suggested that silvery minnows could swim for approximately 9, 15, and 22 min at temperatures of 15, 19, and 23 C, respectively.

A response surface relationship was fit to the data so that predictions of swimming performance could be interpolated between test temperatures (Table 4). Effects of different temperature treatments at long swimming durations may be difficult to detect given the substantial variance in the data and because few fish failed in tests at lower water velocities.

Swim chamber tests, long distance swimming.— Water velocities for longer distance swimming tests were a range of values based on early observations that fish could maintain in the swim chamber for long periods between velocities of about 35 and 50 cm/sec (results above included long distance swimming tests). We progressively increased the duration of long distance testing from 220 min to over 4300 min (72 hours) as we learned more about the swimming performance of this fish.

Rio Grande silvery minnows were capable of swimming at water velocities approaching 60 cm/sec for 220 min or longer. One individual swam at 51 cm/sec for nearly 65 hours and many fish swam at test velocities between 35 and 50 cm/sec for up to 72 hours. We plot data for long distance tests as distance swam, which was obtained by multiplying test water velocity, a rate, by duration of the test, to obtain distance.

Rio Grande silvery minnow were capable of swimming rather remarkable distances in a relatively short time, especially given their small body size (Fig. 15). At all temperatures, silvery minnows were routinely capable of swimming 50 km or more in about 48 hours. Individuals in each of the 15 and 23 C treatments swam over 100 km; one 86 mm TL individual in the 15 C treatment swam 125 km (77.7 miles) in about 73 hours. It is important to remember that those swimming distances were the equivalent of swimming in a static-water environment and that upstream swimming distances in a river would doubtless be less. It is also important to remember that most fish with lower total swimming distances were from tests that were purposefully terminated and likely could have continued swimming; we presented all long distance swim data regardless of test duration for completeness.

We attempted to supplement the long distance swimming data gathered in 15 C tests with a few hatchery fish because additional wild fish were not available. Hatchery fish routinely swam for up to 8 hours but then failed, either because they fatigued or we could not discourage them from remaining near the upper terminus of the swimming chamber where water velocities may have been lower. These relatively large fish should have been good swimmers so their failure in long-distance swimming tests was inexplicable.

Flume tests.— Rio Grande silvery minnow held in the flume orientation chamber were attracted to incoming flows, and within 15 to 240 sec most fish were nudging the upstream barrier screen with their snouts. Upon release, most fish tended to move upstream immediately. The mean proportion of individuals classified as swimmers in all tests was 92%. There were fewer non-swimmers at lower velocities than for high. At test velocities of 8, 23, 38, and 53 cm/sec, 98, 96, 91, and 84% of fish, respectively, were swimmers. Released fish showed no behavioral aversion to swimming over the various-sized substrate particles, including cobble.

The proportion of fish that successfully ascended the flume declined as velocity and substrate particle size increased (Fig. 16). In general, about 50% or more of fish ascended the flume at velocities of ≤ 38 cm/sec. The proportion of fish that successfully ascended the flume during tests at 53 cm/s dropped to about 25 % when averaged over all substrate classes. We modeled the response of proportion of fish that ascended the flume (as logit) as a joint function of velocity and substrate in a response surface regression. The best fit model was one that included main effects of velocity and substrate and their interaction but no higher order (e.g., squared) terms (Table 5). Inclusion of the interaction term was likely a result of the relatively higher proportions of finishers over gravel and cobble substrate at the higher velocities compared to sand.

On average, finish time for fish over sand, gravel, and cobble substrate particles was 264 (4.4 min), 151 (2.5 min), and 266 (4.4 min) seconds, respectively. Average time (\ln Time) for a fish to ascend the flume over sand and gravel substrate increased with velocity (Fig. 17, Table 6). However, time to finish for silvery minnow over cobble substrate was about equal over all test velocities as was demonstrated by the non-significant regression relationship for proportion of fish that finished as a function of water velocity. We modeled finish time (\ln time) as a joint function of velocity and substrate in a response surface regression. The best fit model was one that included main effects of velocity and substrate and their interaction and squared terms. However, the model fit to the data was poor ($R^2 = 0.20$) so we did not present those results.

The maximum distance swam, for fish classified as swimmers that did not completely ascend the flume, averaged 7.8 m over all velocity conditions. This represents just over 50% of the flume length traversed during the 15 min test. Mean maximum distance swam varied little among the different water velocities tested (7.0 to 8.8 m). Similarly, the mean maximum distance swam for fish varied little among the different substrate particle sizes (7.1 to 8.4 m). Those fish and ones that successfully swam the entire flume length generally remained within 10 cm or less of the substrate. Some fish that did not finish the entire flume length rested near or on the bottom.

Denil and vertical slot fishways.—Rio Grande silvery minnows in the Denil and single vertical slot fishway models performed poorly (Table 7). Of the two batches of five fish introduced into the Denil fishway, and the single batch of five fish introduced into the vertical slot fishway, none were observed entering either fishway. Most test animals remained in the downstream pool, attempting to maintain position in the relatively high velocity and turbulent flow. A few fish that encountered the high-velocity shear zone between the downstream pool and the jet issuing from the baffle lost orientation (rolled) and were rapidly displaced downstream. Fish subsequently sought tranquil flow refuges near the bottom of the channel and remained stationary for extended periods.

In contrast, about 50% of fish successfully ascended the dual vertical slot fishway in low velocity tests. Although turbulence made it difficult to track progress of individual fish, upstream swimming must have been immediate and rapid because passage times in the 8 m-long structure averaged about 8 min. Only 8% of fish successfully ascended the dual vertical slot fishway at the high velocity; all of those fish moved through the structure in 5 min or less.

Rock model fishway.—Wild and hatchery-reared Rio Grande silvery minnow successfully negotiated the rock model fishway at both low and high velocity flows (Table 8). In most cases, fish were attracted to the current after release and immediately began swimming upstream. In high velocity tests without the holding pool, some individuals not immediately attracted to upstream flows were impinged on the downstream screen. Addition of the downstream holding pool in subsequent high velocity tests allowed fish to orient and become attracted to flows which reduced impingement rates. In low velocity tests, an average of 74 % of individuals ascended the fishway, compared to only 42% in higher velocity tests conducted without the holding pool. Wild and hatchery fish in higher velocity tests finished the rock model fishway at rates of 42% and 50%, respectively, and time of short-term finishes for each group were nearly identical.

Similarities in performance suggested that hatchery fish were suitable surrogates for wild fish for rock model fishway tests. Presence of the downstream orientation pool in additional high velocity tests reduced impingement and increased the proportion of Rio Grande silvery minnow that finished to 76%, on par with wild fish in the low velocity tests.

Finish times ranged from less than one min up to about 192 hours. Finish times for fish were grouped either as fast (finish time of ≤ 1 hr) or slow (finish time > 1 hr). Fast finish times suggested some Rio Grande silvery minnow sprinted rapidly through the entire structure after release. In all treatment combinations, about 25 to 50% of fish were fast finishers and ascended the model in 7 to 27 min. Fish in the low velocity treatment were, on average, the fastest finishers. The majority of fish had longer finish times. In all treatment combinations, about 50 to 75% of fish were slow finishers and ascended the model in 922 to 2296 min. About half (56%) of the fish in the low flow treatment finished during the day, compared to 65 to 80 % of daytime finishes in any of the high flow treatments.

Observations with underwater cameras showed that Rio Grande silvery minnows moved easily up and down the rock channel. Fish passed upstream through higher velocity gaps between boulders in weirs by utilizing areas laterally adjacent to boulders and swam in the lower velocity boundary layer that existed a few cm over the cobble substrate. Presence of a hypothesized lower velocity boundary layer in the rock channel fishway was substantiated by vertical water velocity profiles measured over similar-sized cobble particles in the flume (Figs. 3-5). There, water velocities in the boundary layer produced by cobbles were reduced, sometimes substantially so, compared to water velocities in the overlying water column.

DISCUSSION

Rio Grande silvery minnow were challenged under a variety of experimental conditions to determine swimming endurance and passage rates. We discuss these results and their implications for fish passage in the following sections.

Swim chamber tests, critical swimming speed estimates.— Results of critical swimming speed experiments showed that fish with short and long acclimation periods performed similarly. These results justified the use of a relatively short 1 hr acclimation period for the remainder of swimming chamber tests. A relatively short acclimation time reduced stress caused by long periods in the swim chamber and eliminated the need for overnight fish acclimation.

Estimates of mean U_{crit} of 51.5 cm/sec and 7.8 body lengths/sec for silvery minnow at 19 C were within the range of estimates for many other species, including salmonids of comparable size (Beamish 1978). For example, four different groups of 89 to 95 mm TL rainbow trout *Oncorhynchus mykiss* had U_{crit} velocities of 36.1 to 41.9 cm/sec, which translated into a swimming rate of 3.7 to 4.4 body lengths/sec. Those rainbow trout tests used a 30-60 min time interval between velocity increases, compared to the 20 min interval used for silvery minnow. The longer interval for rainbow trout may account for the relatively low U_{crit} values compared to silvery minnows. Critical velocity for similar-sized cyprinids emerald shiner *Notropis atherinoides* and spotfin shiner *Notropis spilopterus* was 59 and 23.2-67.2 cm/sec, respectively (Beamish 1978). Swimming rates for the same species were 9.1 and 3.0-8.6 body lengths/sec, respectively. These comparisons suggested that Rio Grande silvery minnows were relatively capable swimmers on par with many other species, including strong-swimming salmonids. Few additional comparisons were available because fish in the 60-90 mm TL size range were not often used as test animals.

The swimming velocity endurance threshold we observed for Rio Grande silvery minnow of 50 to 60 cm/sec was similar to the U_{crit} value of 51.5 cm/sec, which was estimated from independent observations. Although comparisons of U_{crit} and thresholds for longer-term swimming for other species were difficult because few observations were available, the U_{crit} values for Rio Grande silvery minnow may represent a threshold for short-term swimming governed by anaerobic processes and long-term swimming performance governed by aerobic cellular processes. More U_{crit} data gathered at different temperatures would be needed to confirm that Rio Grande silvery minnow U_{crit} swimming performance corresponds to the threshold level.

Swim chamber tests, endurance swimming.– Rio Grande silvery minnow were capable of short-term swimming speeds up to 118 cm/sec, or nearly 17 body lengths/sec. Swimming speeds of Rio Grande silvery minnows measured in body lengths rival those for large-bodied salmonids (Beamish 1978); absolute swimming speeds were lower because the silvery minnows used in these experiments were smaller than most salmonids reported in the literature. Most Rio Grande silvery minnow capable of swimming at 100 cm/sec or more sustained those speeds for 15 sec or less. As water velocity declined from > 100 cm/sec to about 60 cm/sec, swimming endurance increased in a mostly linear fashion in all temperature treatments. A swimming performance threshold was noted at water velocities between about 45 to 60 cm/sec, because swimming endurance times increased sharply at lower velocities. A threshold effect at that velocity may

reflect a shift from anaerobic to aerobic cellular processes that typically occurs during the transition from burst-type swimming to swimming at a more prolonged pace (Beamish 1978). At water velocities in the range of 35 to 50 cm/sec, Rio Grande silvery minnow rarely failed and long-term swimming was possible.

We sometimes observed shifts in swimming behavior of fish tested at velocities near threshold conditions. At the lower end of the velocity range, fish cruised using a steady, but relatively low number of tailbeats; at higher velocities fish were in more of a sprint mode where tailbeats were much more frequent. In both of those modes, fish maintained mostly a single position in the swim chamber. At the intermediate threshold velocities, we observed a saltatory sort of swimming behavior that alternated between cruising and sprinting. As a result, fish would move a short distance upstream during sprinting and drift downstream while cruising. Such a behavior may represent a transition between aerobic and anaerobic cellular respiration.

Temperature had a strong effect on swimming performance, particularly at higher water velocities. The importance of temperature at lower water velocities was diminished because endurance times were high at all temperatures. The union of the upper portions of the predicted endurance relationships where swimming times were greater than 100 min (Fig. 14) likely reflected a point where swimming was sustainable over very long time periods at 15 to 23 C. Predictions for swimming endurance when water temperatures were between the 15, 19, and 23 C levels tested can be estimated from the response surface relationship (Table 4).

Traditional fatigue-water velocity relationships (Beamish 1978, references therein, Peake et al. 1997) that depicted swimming performance of fishes showed distinct break points that corresponded to burst, prolonged, and sustained swimming modes. Burst swimming was typically defined as a time interval of less than 20 sec, prolonged swimming between 20 sec and 200 min, and sustained swimming as a longer, often un-estimated or indefinite time (Beamish 1978). We observed a single velocity threshold in our data, but not one corresponding to time durations of burst, sustained, or prolonged swimming as described above. Instead, our data suggested a continuum between sustained and prolonged swimming rather than a distinct break at 220 min. Incorporating endurance tests for other fishes that are substantially longer than 220 min may show that longer-term swimming performance is best described as a continuum. Rigid, time-based breakpoints between burst and sustained swimming also seemed inappropriate given that water temperature strongly influenced swimming endurance. Breakpoints, if such exist, are likely more taxon-specific and mediated by environmental conditions, so generalities may not be appropriate.

Because swimming speed was a continuum and dependent upon fish length and water temperature, burst swimming speed criteria were not presented. However, we modeled swimming performance as a joint function of those variables so that the reader could make predictions of silvery minnow swimming performance (i.e., burst swimming) that suit their own needs.

Swim chamber tests, long distance swimming.— Rio Grande silvery minnow appeared capable of long-distance swimming within a relatively short time period. We routinely found fish capable of swimming at a rate equivalent to several kilometers in just a few hours of swimming at test water velocities of 50 cm/sec or less. Over longer periods up to 72 hours, we found many silvery minnow capable of swimming, in static water, the equivalent of about 50 km or more. Of course, net upstream movement in a river may be substantially less.

The original study design to estimate long distance swimming capability of Rio Grande silvery minnow was to cycle fish for a swim period (8 to 16 hrs), followed by a rest and feeding period, and continuing that cycle over a period of several days. The negative effects of repeated handling forced a change in the protocol to simply swimming fish continuously for up to 72 hr, which reduced handling stress. We do not view this as a significant change because we were able to obtain several estimates of long-distance swimming capability at all temperatures.

A main reason for conducting long distance swimming tests arose from concerns that silvery minnow may not swim long distances in natural rivers. Although our data suggested that Rio Grande silvery minnow were capable of swimming long distances, several factors may affect the rate of upstream travel in a natural setting. The fastest upstream travel rate is possible when the positive difference between swimming speed of the fish relative to the water velocity in the channel (positive ground speed) is maximized. We have described the swimming capability of Rio Grande silvery minnow reasonably well, but we know little of the distribution of water velocities in a natural channel and how silvery minnow might use them. Environmental variables such as flow magnitude, channel morphology, and substrate type will affect turbulence and velocity characteristics of the water column and these vary by season. We also know little about the swimming behavior of the fish, or the season during which migrations may occur, nor do we know anything about the influence of onset of the reproductive season on movement. Thus, long-distance swimming capability of Rio Grande silvery minnows must be qualified carefully by considering spatial and temporal variation in environmental conditions and fish behavior and physiology that may affect its upstream rate of travel.

Flume tests.— A larger proportion (16%) of Rio Grande silvery minnow released into the flume refused to swim at the highest velocity tested compared to the lowest (4%). The increasing proportion of non-swimming fish at higher velocities suggested that motivation to swim was reduced. This suggested that an optimal passage design would incorporate a relatively low velocity so that the largest number of fish would be motivated to ascend a passage structure. The proportion of fish that successfully ascended the flume declined as velocity and substrate particle size increased. About 50% of the fish tested were able to ascend the flume at velocities of 38 cm/sec or less.

The difference between performance of silvery minnows in the swim chamber and the flume was initially difficult to explain. We expected better performance at higher flume velocities because swim chamber data showed that silvery minnows could swim easily for long periods of time at 50 cm/sec or even higher. At a hypothetical flume velocity of 50 cm/sec, a silvery minnow swimming at 60 cm/sec would require only about 2.5 min to ascend the length of the flume. Because we allowed tests to continue for up to 15 min, we expected larger numbers of fish to finish at the highest velocity, regardless of substrate condition. We suspected that Rio Grande silvery minnow may simply have been comfortable holding position in the flume and were not motivated to swim upstream. Fatigue curves for different swimming passage distances, which are presented in the Applications section of this report, may support this hypothesis. Those relationships suggested that upstream passage of the 14.6 m-long flume flowing at 53 cm/sec, the highest velocity tested, was within the swimming performance capability of most silvery minnows we tested. Rock channel results suggested some fish simply took longer to finish, which suggested that longer flume tests likely would have resulted in more finishes.

Time required to ascend the flume with sand or gravel substrate generally increased with water velocity, but was about equal for all velocities in tests with cobble substrate. Observations of fish behavior during flume tests suggested reasons for reduction in proportion of fish that ascended the flume as particle size increased. When fish were released into the flume over sand substrate, movement was usually immediately upstream, directed, and because of the absence of velocity breaks created by gravel and cobble particles, fish were swimming nearly constantly. When fish were released into the flume with cobble substrate, they were much more likely to swim for a time, sometimes via an upstream sprint, and then find a velocity break in or behind a cobble particle. Unless motivated to move by probing with a glass rod, fish would maintain position for long time periods. The lower proportion of fish that finished in tests over cobble

substrate at any velocity, and the lack of relationship between finish time of fish and velocity with cobble substrate suggested fish were comfortable holding position or were not motivated to move upstream. We presumed that fish would eventually finish, but may simply take a longer time. This notion was supported by data from the rock model fishway, which suggested that 50% or more of individuals in those tests had finish times of 1 hr or more.

Denil and vertical slot fishways.—Rio Grande silvery minnow performed poorly in Denil and single vertical slot fishway models. Fish were observed having difficulty moving from the tailwater into the higher velocity baffle flow. Swimming orientation was typically lost when fish encountered the velocity shear zone between the downstream pool and the jet issuing from a baffle constriction. Turbulence resulted in uncontrolled displacement of fish in the flow field; fish then sought tranquil flow refuges near the bottom of the channel and remained stationary for extended periods. We ran only a small number of tests in each of these model types because of limited fish availability and because the likelihood of success for additional releases seemed low.

Performance of Rio Grande silvery minnow was better in the dual vertical slot fishway, but only at low velocities. Fish oriented quickly and immediately swam upstream. This was likely due to the absence of large eddies and high-velocity turbulent flows present of the Denil and single vertical slot fishways. Flow in high velocity trials in the dual vertical slot fishway was very turbulent. Fish often encountered swift lateral and vertical flow vortices, which caused fish to seek refuge on the bottom until the end of the trial.

Others have tested Denil and vertical slot fishways in a natural setting. For example, Schwalme et al. (1985) captured thousands of relatively small-bodied spottail shiner *Notropis hudsonius* that passed through a vertical slot fishway on the Lesser Slave River, Canada, and many were observed passing through 10 and 20% gradient Denil fishways. Average velocities in those fishways were about 100 cm/sec or less; lowest fishway velocities were not reported but fishway entries appeared tranquil. Swimming performance data were not available for spottail shiners. Spottail shiners captured were in reproductive condition and may have been motivated to move upstream in that study. However, even though large numbers were captured, probability of a fish encountering a fishway and ascending it was unknown. It may be too, that turbulence characteristics were different at the entry of Lesser Slave River fishways than the ones we used.

Rock model fishway.—Performance of Rio Grande silvery minnow in the rock channel fishway at low and high water velocities was better than in the Denil fishway, or either of the two vertical slot fishways. Water velocity affected the proportion of fish that finished in high velocity

tests only when a downstream holding pool was not available. In both low and high velocity tests where a holding pool was available, about 75% of fish successfully ascended the rock channel fishway. Average short-term finish times were lower in low velocity tests than in high. Average long-term finish times were similar in all tests except for the hatchery fish in high velocity tests ($N = 2$) in the absence of a holding pool, which were lower. Likely reasons were small sample size and that any fish that were going to finish were relatively strong swimmers and were likely to finish quickly. Many of the remaining non-finishers were impinged downstream at the beginning of tests which shortened the average passage time of all fish.

The proportion of fish that finished in short or longer times was roughly equivalent in all test conditions. In general, 25 to 50% of fish were short-term finishers, usually 30 min or less. The remaining 50 to 75% of fish were classified as longer-term and took an average of 32 hr to finish. Those longer-term finish times were likely overestimated because finish time was recorded when the head box was checked at intervals. This would not account for fish that finished between monitoring intervals, which would have resulted in shorter finish times. Differences in finish times may reflect different fish behaviors or differences in swimming capability of individuals.

Rio Grande silvery minnow generally finished tests during daylight hours, but a reasonable proportion of fish appeared active at night as well. This was particularly true for fish in low velocity tests and may reflect more nocturnal behavior of some individuals. The number of long-term and nighttime-finisher fish may be spuriously correlated. This was because all fish were released during the day so fish with a propensity for nighttime movements would likely also be longer-term finishers.

Although we have no substantiating video, Rio Grande silvery minnows with longer or nighttime rock channel fishway finish times almost certainly needed to rest in low- or zero-velocity areas in the channel. We observed such resting behavior in the flume, where silvery minnow would occupy velocity breaks created by gravel or cobble particles or use the boundary layer to maintain position with minimal swimming. Vertical water velocity profiles measured in the flume over cobble particles similar in size to those in the rock channel suggested presence of water velocities ranging from near zero up to the nominal testing level. A mosaic of water velocities also existed in the horizontal dimension of the rock channel fishway as well, because lateral margins were of low velocity compared to areas of fast-flowing water between mid-channel boulders.

Presence of a mosaic of water velocities in lateral and vertical dimensions that fish can choose to swim through is a main difference between the rock channel fishway and other structures such as Denil or vertical slot fishways. In the rock channel fishway, Rio Grande silvery minnow can and do use the boundary layer created by the cobble particles and may also use low-velocity channel margins to reduce energetic demands of swimming upstream. We presumed that boundary layer velocity conditions in the rock channel fishway were similar to those in the flume (Figs. 3-5), since sizes of cobble particles used in each were similar. Silvery minnow avoidance of the highest velocity areas in the rock channel fishway likely conserved energy and enhanced the likelihood of finishing the trial. In the vertical slot fishways, lower velocity resting areas exist on the floor between the baffles. However, successful upstream passage in those fishways requires that fish traverse the slot in the baffles, the highest velocity area in the fishway. Ability of Rio Grande silvery minnow to avoid high velocity areas of the rock channel fishway may be the reason those fish were more successful at passage compared to fish in tests of other fishway designs.

Fishway attraction.- The nature of flows needed to attract fish to enter fish passage structures is important because without attraction, no passage is possible. For salmonids, strong turbulent flows are often needed to attract fish to enter passage structures. However, as previous tests have shown, prevailing theory built on tests conducted with large-bodied salmonids may not be transferable to small-bodied Rio Grande silvery minnow. Although we did not directly assess attraction flow characteristics, observations of fish in experiments and fishway models provides some insights.

In general, fish at rest or swimming at low velocities were generally motivated to swim when higher velocities were encountered. This was true in the swimming chamber, and for fish released into the flume and certain fishway models. In those cases, flow was typically tranquil not turbulent. Sometimes, an acclimation area was needed to orient fish when the transition was from a low velocity environment into a high one. This was evidenced in the rock channel fishway, where fish performed better when first allowed to orient in the lower velocity downstream pool rather than being immediately subjected to higher velocity flows of the channel. Thus, an increase in flow velocity seemed to attract fish from lower velocity areas or motivated fish swimming at low velocity to swim faster. Poor passage success of Rio Grande silvery minnows introduced into Denil and single vertical slot fishways may be due, in part, to high flow turbulence and velocity shears present both in the fishway and immediately downstream. Collectively, data and

observations suggest that attraction flows should be relatively constant and tranquil, and of slightly higher velocity than those present in the pool where fish are holding.

Applications for fishways.—Traditional fishway designs have not usually considered species with a body size as small as Rio Grande silvery minnow. Thus, existing literature on fishway designs was of limited use when considering design constraints and criteria for a fishway designed for passage of Rio Grande silvery minnows. A combination of swimming performance and behavioral attributes of silvery minnow need to be considered and engineered into a passage structure to enhance the probability that fish will successfully use it.

Successful ascent of a fishway depends in part on the ability of the fish to maintain a speed higher than the water velocity in the passage channel. This may allow the fish to achieve a positive ground velocity for a long enough period to swim between resting areas in the fishway or to pass the fishway completely. Naturally, tradeoffs exist between swimming speed of the fish and endurance because they are inversely related; performance may also be related to fish body length and water temperature. An equation in Peake et al. (1997) was parameterized with data collected in this study, and was used to predict fishway water velocities that will permit passage of Rio Grande silvery minnows, given the length of the fish, water temperature, and the length of the fishway. The equation is of the form:

$$V_{\text{fishway}} = V_{\text{swimming}} - (D C E_s^{-1}), \quad (2)$$

where V_{fishway} is maximum allowable fishway water velocity (cm/sec), V_{swimming} is swimming speed of the fish (cm/sec), D is fishway length (cm), and E_s is silvery minnow endurance (sec) swimming at V_s . E_s was determined from response surface equation parameters (Table 4), which was used instead of non-linear regressions because effects of water temperature and fish body length can be jointly estimated as well. We assumed a fishway length, D , of 50 m, water temperature of 19 C and solved for the relationship at a range of fishway water velocities using fish that were either 6, 7, or 8 cm TL. Effects of 15, 19, and 23 C water on swimming performance of a 7 cm TL fish was also estimated over a range of fishway water velocities.

Maximum flow velocities that allowed fish 6, 7, and 8 cm TL to ascend a 50 m long fishway were 43.6 (48.9), 45.5 (51.1), and 47.6 (53.4) cm/sec, respectively (Fig.18). Parenthetical numbers behind each fishway velocity for each fish length was the speed that fish

had to maintain in order to pass the length of the fishway before it fatigued. Similarly, maximum flow velocities that allowed a 7-cm-TL fish to ascend a 50-m-long fishway in water temperatures of 15, 19 and 23 C were 42.9 (49.1), 45.5 (51.1), and 48.3 (54.3) cm/sec, respectively (Fig. 19). Swimming velocities needed for fish to pass the fishway were affected by fish length and temperature in a predictable manner. Swimming velocities for passage were all in the range of the threshold effect (45 to 60 cm/sec) noted earlier where swimming endurance changes rapidly with swimming chamber velocity. Swimming velocities in that range optimize the tradeoff between maximizing endurance time and maximizing the velocity in a 50-m-long fishway. Estimating a maximum suitable fishway velocity is important so that the shortest fishway length that allows passage can be defined. These relationships assume that fish swim constantly at that pace, swim directly into the fastest current, and do not rest. We know from other experiments and observations that these are unlikely behaviors, but results of these equations give managers some conservative expectations for silvery minnow performance under a variety of conditions. Predictions about where fish swim in the water column relative to a distribution of water velocities along a vertical profile, and other questions that involve detailed aspects of fish behavior, were beyond the scope of this project.

Swimming passage distance, water velocity, and velocity-dependent fatigue relationships are the interrelated components needed to determine whether Rio Grande silvery minnow successfully complete a swimming challenge, under a constrained set of conditions. We solved equation 2 above for passage distances ranging from 50 to 10,000 cm, and then plotted maximum flow velocity that would allow passage of 6, 7, and 8-cm-TL fish as a function of those same passage distances in water at 19 C (Fig. 20). Results showed that maximum water velocities in even moderate length fishways (e.g., 2000 cm) need to be constrained to less than 50 to 60 cm/sec to allow passage of silvery minnows, given the aforementioned assumptions. Water velocity to achieve a relatively short upstream swimming distance of 50 cm was 83 to 103 cm/sec, depending on fish size. Swimming speed of the 8 cm TL fish to achieve that distance was unknown because the relationship never achieved an asymptote. Swimming rate to achieve that distance was likely over 110 cm/sec, near the maximum swimming we observed in the swim chamber of 118 cm/sec.

Solving for such relationships over a variety of passage distances permit predictions of the maximum fishway water velocity that would allow fish to swim a given distance upstream. This was of interest because passage rates observed in relatively short laboratory fishway models may be much shorter than ones that might be built in the Rio Grande. For example, the laboratory rock

channel fishway had a 2% gradient but would rise only about 0.46 m over its 23 m functional length. Therefore, building a rock channel fishway with a 1% gradient around a hypothetical diversion dam 3.05 m high would require a straight channel fishway length of about 306 m. Predictions of these equations for shorter-distance swimming under sprint swimming speeds may also be useful for design considerations. For example, given a certain average fishway flow velocity, the sprint distance of a fish could be predicted so that spatial distribution of low-velocity resting pools was optimized. Predictions for very high challenge velocities could be used to determine if silvery minnows could pass through slots in fishway baffles of a given velocity.

Given that certain fishway designs would need to be quite long to ascend actual barriers, and that fish may have to sprint to overcome nominal fishway water velocity to pass upstream, resting pools or velocity breaks may be needed at appropriate intervals. Other considerations also promote the notion that fish should move through the fishway as fast as possible. For example, longer passage times may also expose fish to increased predation from wading birds.

An uncertainty in use of predictions of fishway velocities and swimming distances is how silvery minnows actually utilize the channel and the boundary layer. As was previously hypothesized, the mosaic of water velocities present in the rock channel fishway presented fish an opportunity to seek the lowest velocity environment as they progressed upstream. In the absence of better information on swimming behavior of silvery minnow, predictions of swimming distance and maximum channel velocity may provide managers with a conservative estimate of constraints to be considered in construction of structures designed for upstream passage of silvery minnows in the Rio Grande.

Constraints of fishway velocities in baffled structures are less problematic because actual passage velocities through slots can be measured. However, additional consideration must be given to calculation of energy dissipation indices between baffles, and accounting for effects of high turbulence and strong eddies which may influence fish swimming behavior and passage rates.

RECOMMENDATIONS

This research was conducted to define design parameters for a fishway constructed to allow passage of Rio Grande silvery minnow in the central Rio Grande, New Mexico. Because these data address mostly design considerations, the ultimate decision to construct a fishway should be

based on a compendium of other supporting information. Nevertheless, results of our swimming performance experiments and those from testing several fishway models support the notion that Rio Grande silvery minnow are fairly capable and motivated swimmers. It follows that if a structure is engineered around the constraints imposed by the physiology and behavior of Rio Grande silvery minnow, and if environmental conditions (temperature, timing) at the time of passage are favorable, a structure may enhance passage capability of a portion of the population.

Several types of structures were tested. Overall, performance of fish in the Denil and single vertical slot fishways was poor, likely because fishway velocities were high and flows were turbulent. Performance of silvery minnow in a dual vertical slot fishway at low velocity was relatively good, but declined at a higher velocity. Performance of fish in the rock channel fishway was best, from a standpoint of the number of successful finishes, if a low-velocity holding and orientation pool was present.

General recommendations for design of any fishway type are listed below, and are followed by supporting information.

- Maximum velocities encountered by fish for even very short time periods (e.g., 10 sec) should not exceed about 100 cm/sec at 23 C and about 80 cm/sec at 15 C.

Although silvery minnow were capable of swimming at velocities > 80 to 100 cm/sec in the swimming chamber, fatigue time was short and maximum upstream distance traveled (Fig. 20) was limited at high velocities. Also, passage in the dual vertical slot was moderate in lower flow tests with in-slot velocities of about 78 cm/sec, but very low at 87 cm/sec, further supporting the recommended maximum fishway velocity. The relationship between flow velocity and turbulence resulting in strong shear zones is poorly defined for fishways. Tests suggested that turbulence disruptive to passage was less likely when passage velocity was less than the recommended maximum. Unlike baffled fishways, silvery minnow were able to pass upstream in the rock channel fishway where maximum velocities between boulders were comparable or even higher (> 100 cm/sec). This was likely possible because silvery minnow were able to use a constant near-boundary flow of reduced velocity to pass upstream.

- Provide a mix of flow velocities in the fishway, either via a refuge, resting pool(s), boundary layer, or all of the above.

A mix of flow velocities allows silvery minnow to choose the most energetically efficient path to pass the fishway, and should provide for a wider range of life stages to pass, should they be motivated to do such. If fishway length is excessive, resting pools will give fish a place to recover.

- Maximum velocities in baffled fishway slots should not exceed about 50 to 80 cm/sec, depending on fishway length.

Swimming chamber and fatigue curves showed that silvery minnow performance was reduced at water velocities greater than 50 to 60 cm/sec, although short bursts at higher velocities were possible. Substantial upstream swimming would be possible only when fishway velocities were lower than 50 to 60 cm/sec. Velocities of 50 cm/sec in baffles should allow for relatively small fish to pass, and would also assist with passage of larger fish if water temperatures were below 15 C. Tests in the flume, the dual vertical slot, and endurance curves support the idea that 50 cm/sec water velocity would allow most motivated fish to pass a fishway. Maintaining lower velocities is also important if fish are motivated to swim the entire length of the fishway in one effort. Such would reduce the chance of disorientation of fish in the fishway. Higher velocities would require suitable resting areas for silvery minnow at appropriate intervals. Fishway velocity, fishway length, and swimming speed relationships could guide placement of such areas if needed.

- Maximum water velocities in shorter rock channel fishways should not exceed about 100 cm/sec, or about 75 cm/sec in longer ones, provided there is substantial lower velocity boundary areas, boulder velocity breaks, channel margins, or resting pools. A channel gradient less than 1.25 percent is recommended.

The majority of Rio Grande silvery minnows tested in the rock model were able to pass it in relatively low (50 to 75 cm/sec) or higher (75 to 100 cm/sec) maximum flow velocities. Successful passage was likely a function of presence of ample low velocity areas that fish could pass upstream through. A main uncertainty from laboratory studies that used a relatively short rock channel is how fish in the wild would respond to a much longer structure. Fishway velocity, fishway length,

and swimming speed relationships could guide managers on issues of probability of successful silvery minnow passage for different fishway lengths.

- Consider larger, cobble-sized substrate particles in fishways.

Although silvery minnow performed well in the flume over a variety of substrate particle sizes ranging from sand to cobble, cobble appeared to have a number of benefits. First, observations showed that silvery minnow were not averse to swimming over it. Second, silvery minnow used the boundary layer and low velocity zones behind cobbles to rest or make upstream progress. Third, cobble may provide a more natural array of cover that resting fish could seek refuge in.

- Attraction flow velocity should be somewhat faster than the water into which it flows.

This recommendation assumes that attraction flows enter a semi-quiescent pool below a diversion dam where Rio Grande silvery minnow are congregated. The increased velocity over ambient may attract silvery minnow to swim up the fishway. Fish seemed attracted and responsive when flows in the swimming chamber increased. Silvery minnows also seemed attracted to increased flow velocity in the flume and the rock model, especially when there was a downstream holding pool. The attraction area should be placed where most silvery minnows would be expected, likely just below the diversion dam.

- Attraction flows should be tranquil, not turbulent.

Tests in a number of fishways showed that silvery minnow were generally uncomfortable in visibly turbulent flows and generally avoided them.

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Table 1. Recent examples of rock fishways constructed by the U. S. Bureau of Reclamation that were designed for non-salmonid fish passage.

Type	Fishway	Elevation Gain, ft	Fishway Slope Percent	Status
Rock Ramp or Channel	Marble Bluff Dam, Truckee River near Nixon, Nv.	1.5	0.3	Constructed in 1998
Rock Channel with Pool and Riffle	Pyramid Lake Fishway, Experimental Bypass Channel	12	0.58/1.4 0.96/1.6 (pool/riffle)	Constructed in 1996
Rock Channel with Pool and Riffle	Grand Valley Irrigation Company Diversion Dam, Colorado River near Grand Junction, Co.	5	0.9/1.3	Constructed in 1997
Rock Channel with Boulder Weirs	Huntley Diversion Dam, Yellowstone River, Billings, Montana	8	1.8	Constructed in 1999
Rock Channel with Boulder Weirs	Derby Diversion Dam, Truckee River, Reno, Nevada	17	1.6	Constructed in 2002

Table 2. Mean U_{crit} values and mean body lengths/sec swum (BL/sec) swum at U_{crit} speed for Rio Grande silvery minnow acclimated for short (mean time = 133 min) and longer (mean time = 860 min) time periods at 19 C. T-test p-values test the hypothesis that mean values are not significantly different between short and longer term acclimation times.

Parameter	Short-term acclimation	Longer-term acclimation	t-test p-value	Overall mean
U_{crit} (cm/sec)	50.2	52.8	0.73	51.5
(SE, N)	(11.79, 6)	(12.93, 6)		(7.80, 12)
BL/sec	7.8	7.8	0.73	7.8
(SE, N)	(1.61, 6)	(1.23, 6)		(1.36, 12)

Table 3. Non-linear regression relationships of swimming endurance as a function of swimming chamber water velocity at 15, 19, and 23 C test temperatures. β_0 and β_1 are intercept and slope parameters, respectively, in regression relationships of the form:

$y = \beta_0 * (\exp - \beta_1 * X_i)$, where $y = \ln(\ln(\text{min swimming endurance} + 1)) + 1$, and X_i is swimming velocity. P -values test the hypothesis that the slope of the regression relationship is significantly different than zero, r^2 values were estimated as $1 - (\text{residual sums of squares}/\text{corrected total sums of squares})$.

Temperature treatment	df	β_0 (95% CI)	β_1 (95% CI)	r^2	p-value
15 C	35	4.257 (2.956 - 5.558)	0.0514 (0.0386 - 0.0641)	0.78	< 0.0001
19 C	52	2.980 (2.610 - 3.349)	0.0324 (0.0272 - 0.0376)	0.84	< 0.0001
23 C	45	2.987 (2.617 - 3.357)	0.0299 (0.0250 - 0.0348)	0.86	< 0.0001

Table 4. Least squares general linear model coefficient estimates, significance probabilities, and Type III sums of squares for a response surface regression relating swimming endurance (as $\ln(\ln(\text{min swimming endurance} + 1)) + 1$), as a function of water temperature (T), water velocity (V), and fish total length (TL).

Parameter	df	Coefficient		Type III	
		estimate	SE	SS	<i>p</i>
Intercept	1	3.46	0.4351	–	< 0.0001
Velocity (V)	1	- 0.0856	0.0067	763.8	< 0.0001
V ²	1	0.00040	0.00004	383.4	< 0.0001
Temperature (T)	1	0.0303	0.0080	68.3	0.0002
TL	1	0.0883	0.0362	27.9	0.0163

^a Swimming endurance model statistics: df = 5, 122, model $F = 184.3$, $R^2 = 0.86$, $p = < 0.0001$.

Table 5. Maximum likelihood general linear model coefficient estimates, significance probabilities, and chi-square statistics for a regression model estimating probability (as logit) of a Rio Grande silvery minnow swimming the length of the flume as a function of water velocity, substrate size (mm), and substrate X velocity interaction (sv).

Parameter	df	Coefficient estimate	SE	Chi-square	Pr > ChiSq
Intercept	1	2.6818	0.5681	22.28	< 0.0001
Velocity	1	-6.9561	1.5327	20.60	< 0.0001
Substrate	1	-0.0110	0.0055	4.05	0.0441
S x V	1	0.0239	0.0153	2.45	0.1175

Table 6. Least squares regression coefficient estimates, significance probabilities, and fits (r^2) for models of the time for Rio Grande silvery minnow to swim the length of the flume as a function of water velocity over sand, gravel, and cobble substrate.

Substrate	df	Intercept (se, p)	Slope (se, p)	r^2	Regression p -value
Sand	35	4.03 (46.35, 0.93)	865.6 (180.8, <0.0001)	0.40	< 0.0001
Gravel	35	63.85 (43.86, 0.15)	296.4 (139.5, 0.04)	0.12	0.04
Cobble	29	302.13 (82.8, 0.001)	-150.8 (280.8, 0.60)	0.01	0.60

Table 7. Mean proportion of Rio Grande silvery minnow that ascended the entire length of the Denil ($N = 2$ releases, $N =$ five individuals), single vertical slot ($N = 1$ release, $N =$ five individuals), and dual vertical slot fishways in low velocity ($N = 5$ releases) and high velocity ($N = 4$) flow conditions ($N = 10$ fish per release). Parenthetical values are ranges. Low velocity was 70 cm/sec, high velocity was 100 cm/sec. Wild fish were used in Denil and single vertical slot tests; hatchery fish were used in tests of the dual vertical slot fishway.

Parameter	Denil fishway	Single vertical slot fishway	Dual vertical slot fishway	
			Low velocity	High velocity
Proportion finished	0.0	0.0	0.52 (0.10 to 1.0)	0.08 (0.0 to 0.20)
Average time (min), all finishers	–	–	8.2 (0.9 to 18.7)	2.6 (0.6 to 4.6)

Table 8. Mean proportion of Rio Grande silvery minnow that ascended the entire length of the rock model fishway for low (about 50 to 75 cm/sec) and high (about 75 to 100 cm/sec) flow conditions. Low velocity, wild fish were released in a downstream pool created by tailboards, high velocity wild fish, no pool were released into current at the downstream end of the fishway. The rock channel fishway was then modified to create a downstream holding pool so other high velocity test fish (hatchery fish were the only ones available) were released in a low velocity environment that allowed for more orientation time prior to ascending the fishway. Either 10 or 15 fish were released for each test. Mean proportion of fish that finished in short (≤ 1 hr) and longer-term intervals (> 1 hr) and their average finish times are for all individuals in all tests. Proportion of daytime finishes was the total number of fish observed in the head box during daytime hours (0600 to 1800 hrs) relative to the total number observed; the complement would be the proportion of night time finishes. Parenthetical values are ranges.

Parameter	Low velocity, wild fish ($N = 4$)	High velocity, wild fish, no pool ($N = 4$)	High velocity, hatchery fish, no pool ($N = 2$)	High velocity, hatchery fish, pool, ($N = 6$)
Proportion finished	0.74 (0.65 - 0.87)	0.42 (0.29 - 0.62)	0.50 (0.40 - 0.60)	0.76 (0.50 - 0.90)
Proportion short-term	0.38	0.50	0.27	0.26
Proportion long-term	0.62	0.50	0.73	0.74
Average time (min), short-term finishers	7 (1 - 41)	21 (3 - 57)	23 (2 - 60)	27 (1 - 60)
Average time (min), long-term finishers	2223 (95 - 7200)	2213 (63 - 11520)	922 (109 - 2080)	1870 (96 - 7200)
Proportion daytime finishes	0.56	0.80	0.65	0.72

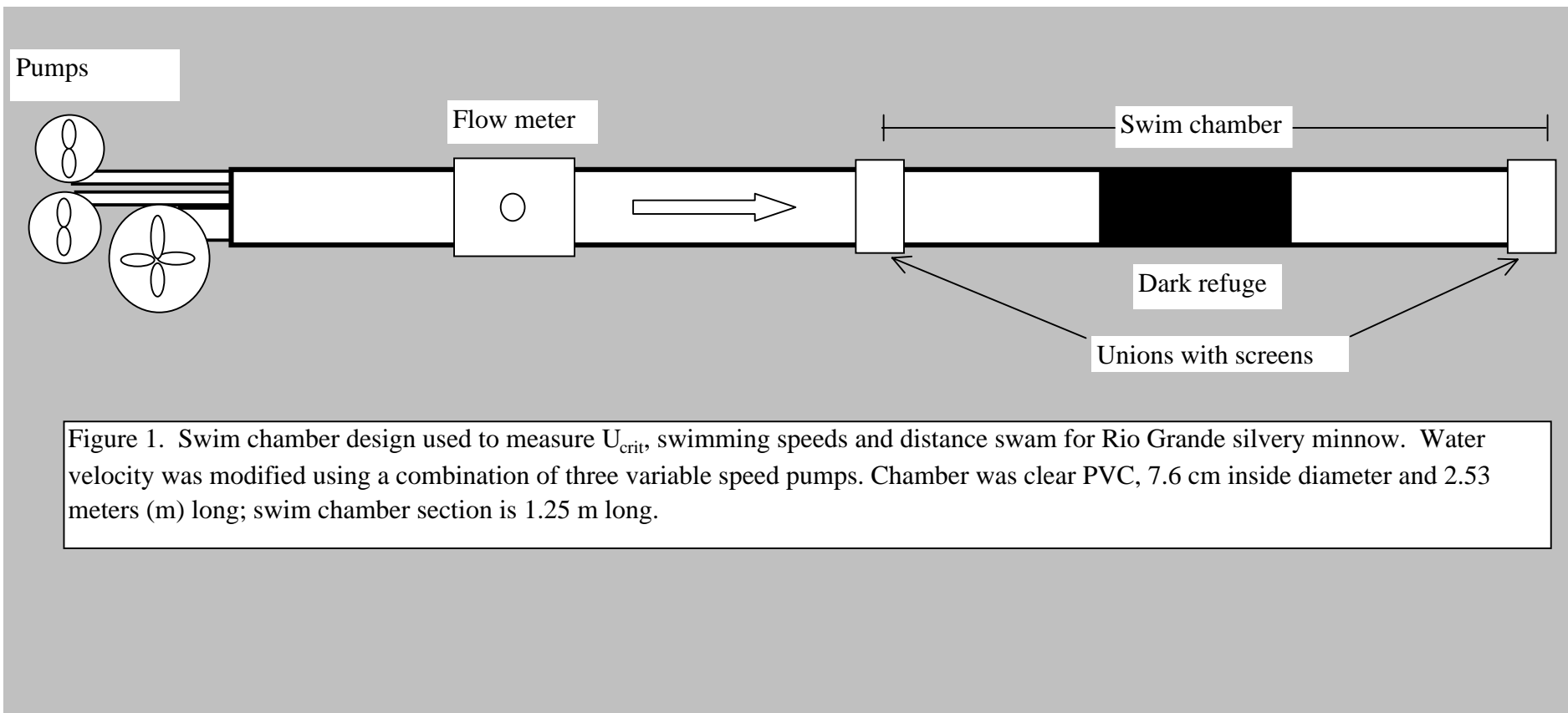
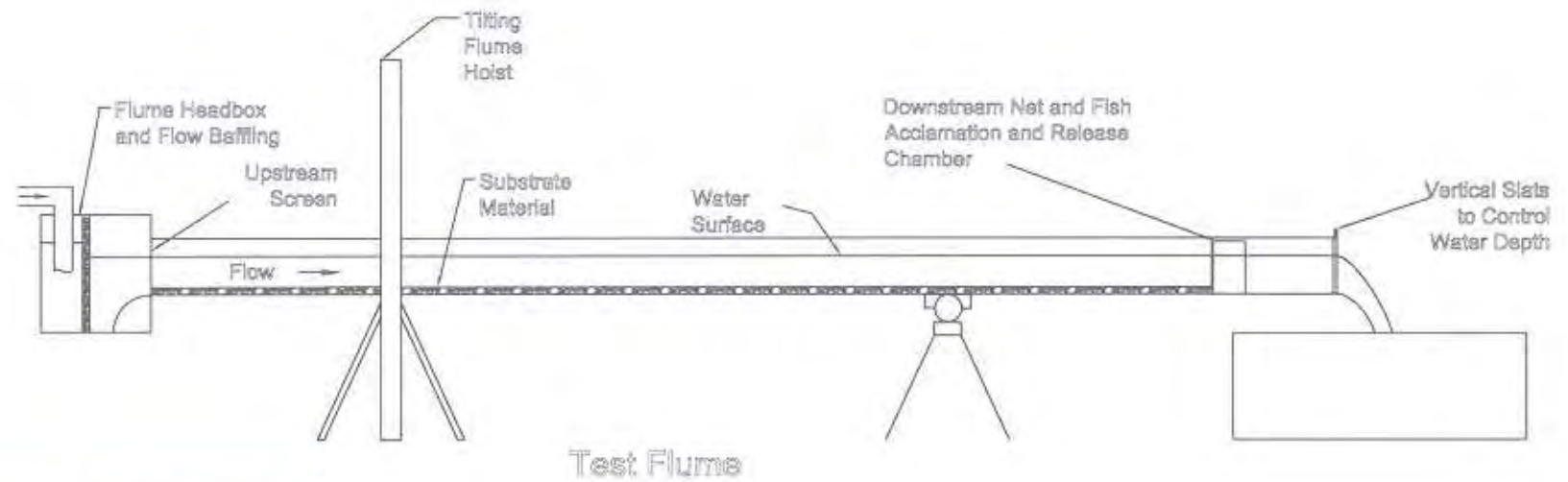


Figure 1. Swim chamber design used to measure U_{crit} , swimming speeds and distance swam for Rio Grande silvery minnow. Water velocity was modified using a combination of three variable speed pumps. Chamber was clear PVC, 7.6 cm inside diameter and 2.53 meters (m) long; swim chamber section is 1.25 m long.



View looking down test flume



Course-sand channel bed roughness



Gravel channel bed roughness



Cobble channel bed roughness

Figure 2. Test flume used for volitional swim tests over different bed roughnesses.

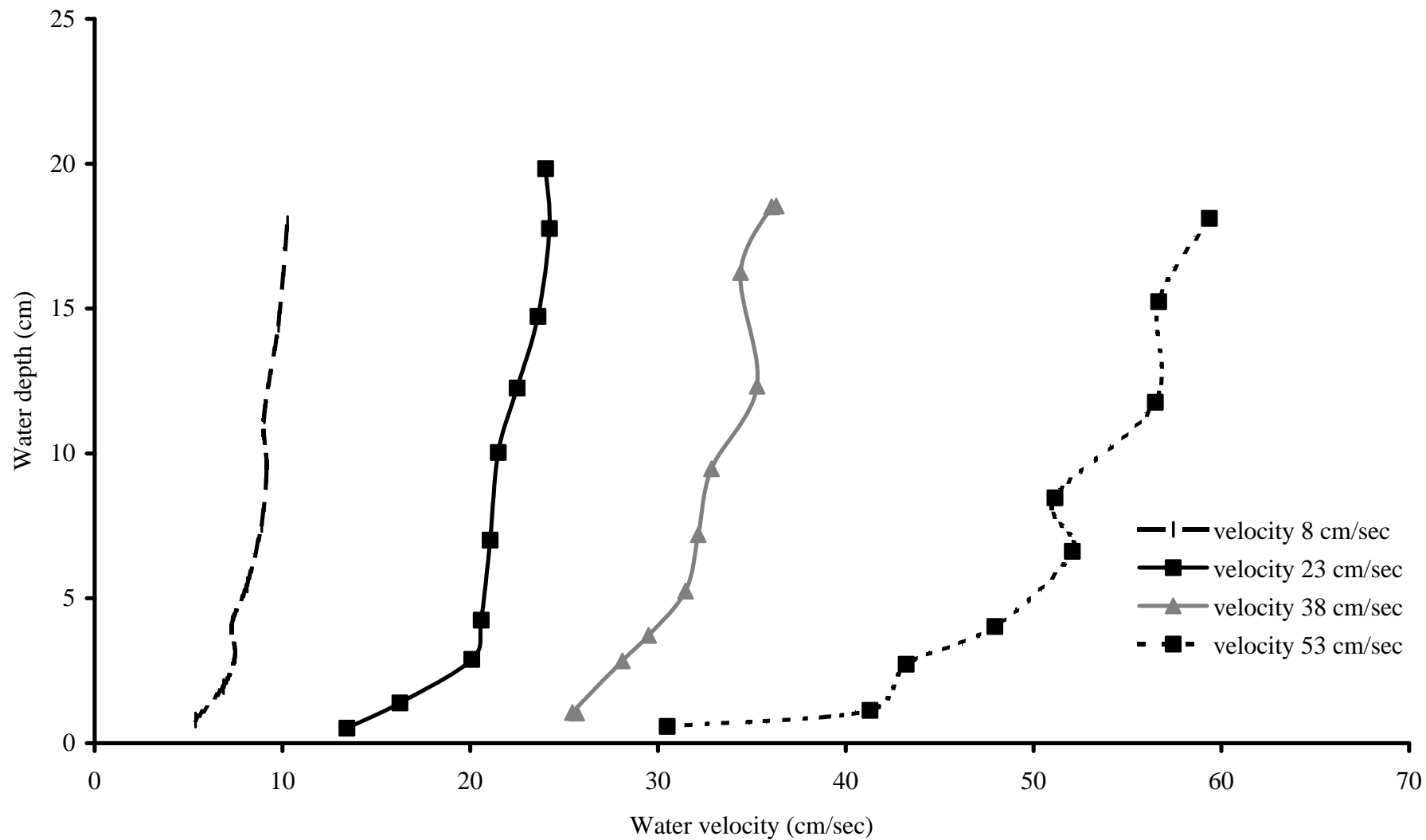


Figure 3. Vertical velocity profiles for flume channel with sand bed flowing at target velocities of 8, 23, 38 and 53 cm/sec.

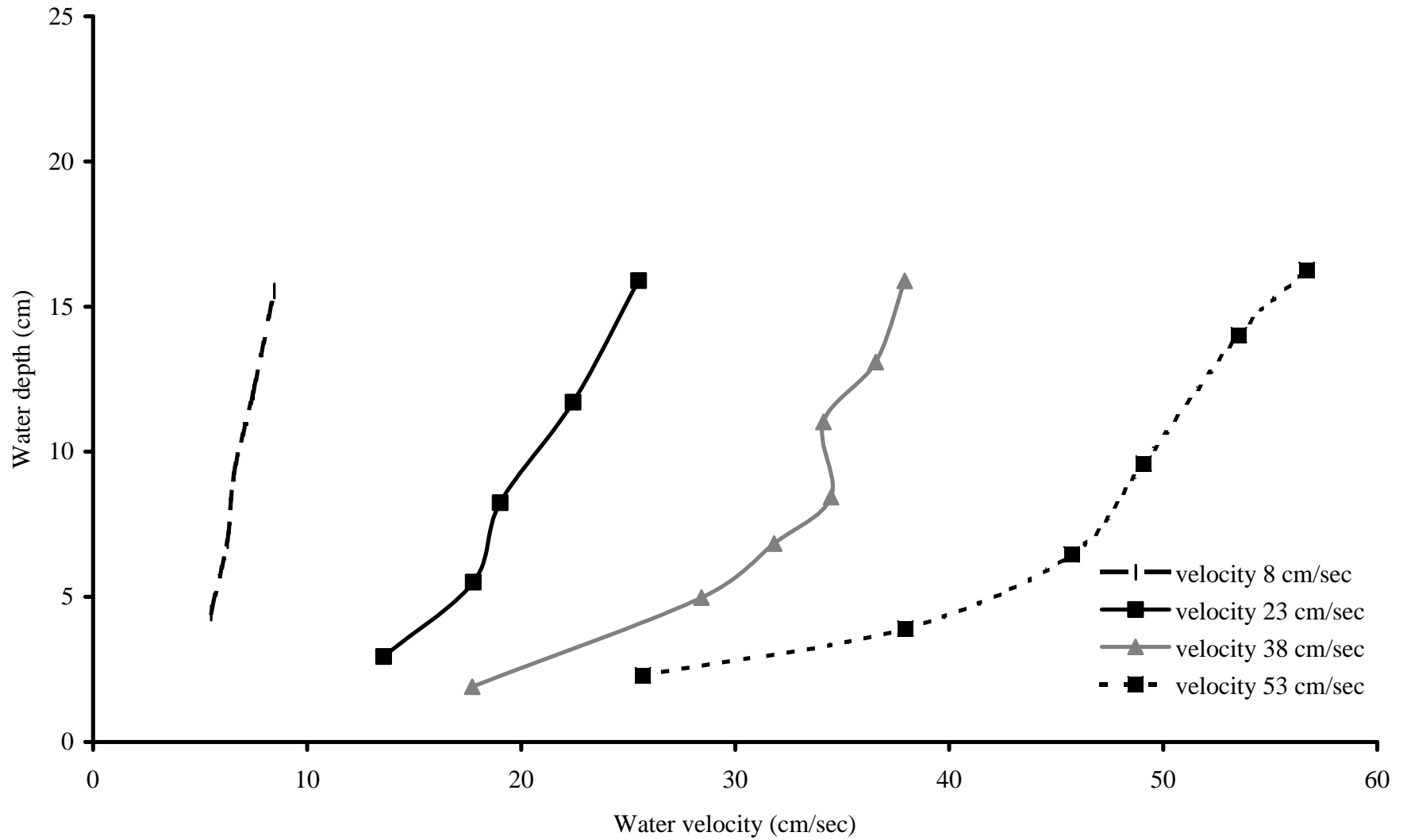


Figure 4. Vertical velocity profiles for flume channel with gravel bed flowing at target velocities of 8, 23, 38, 53 cm/second.

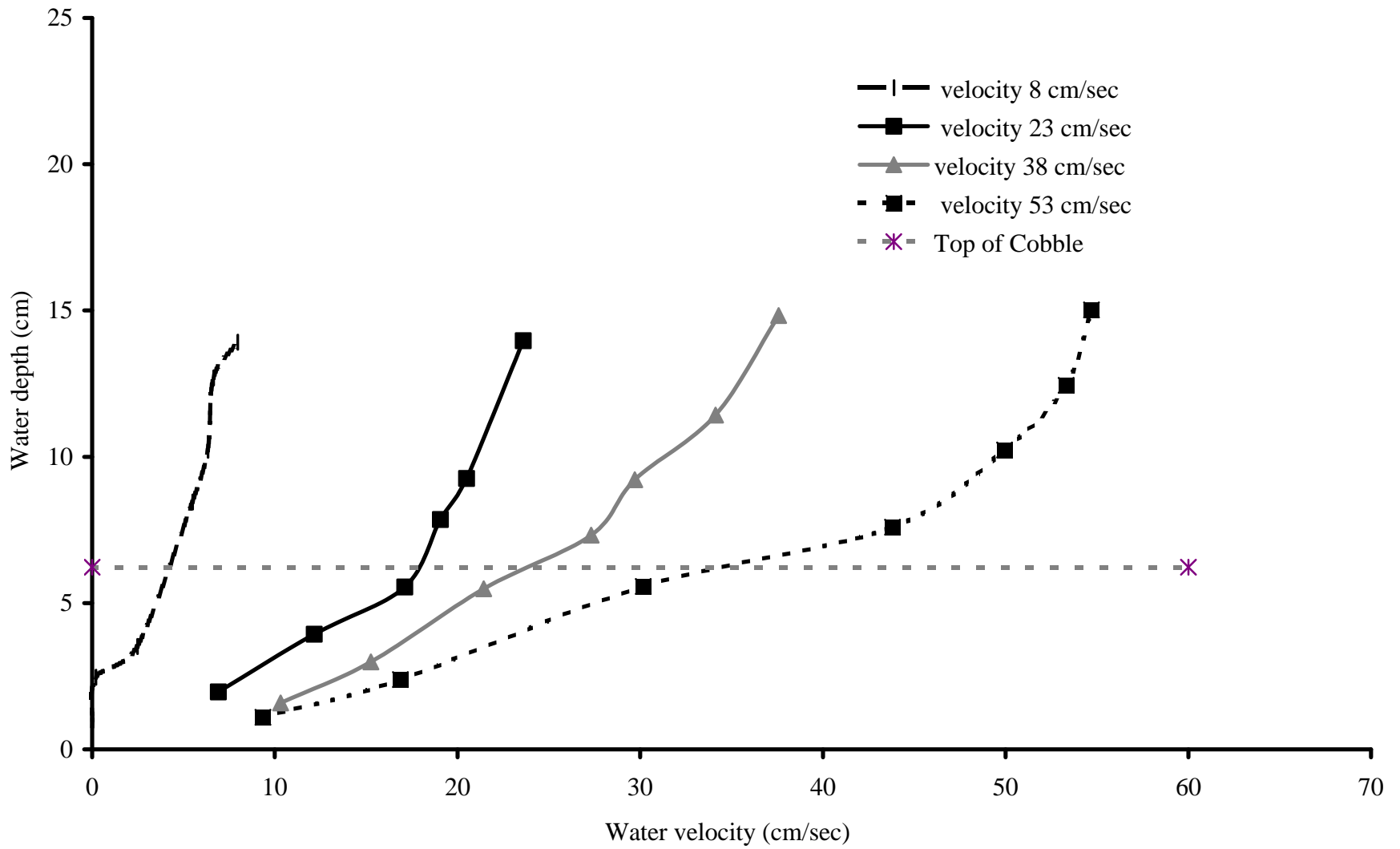
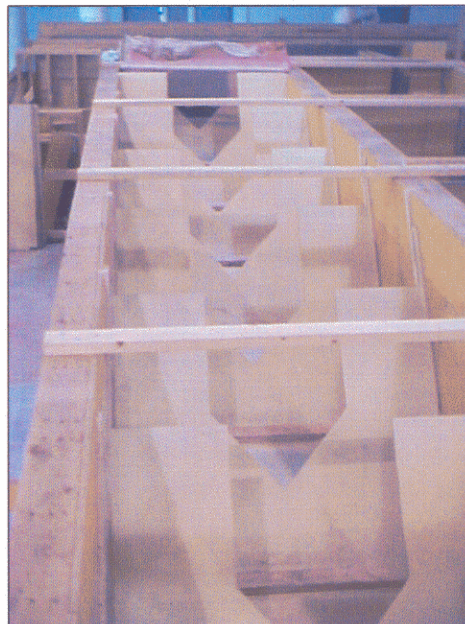
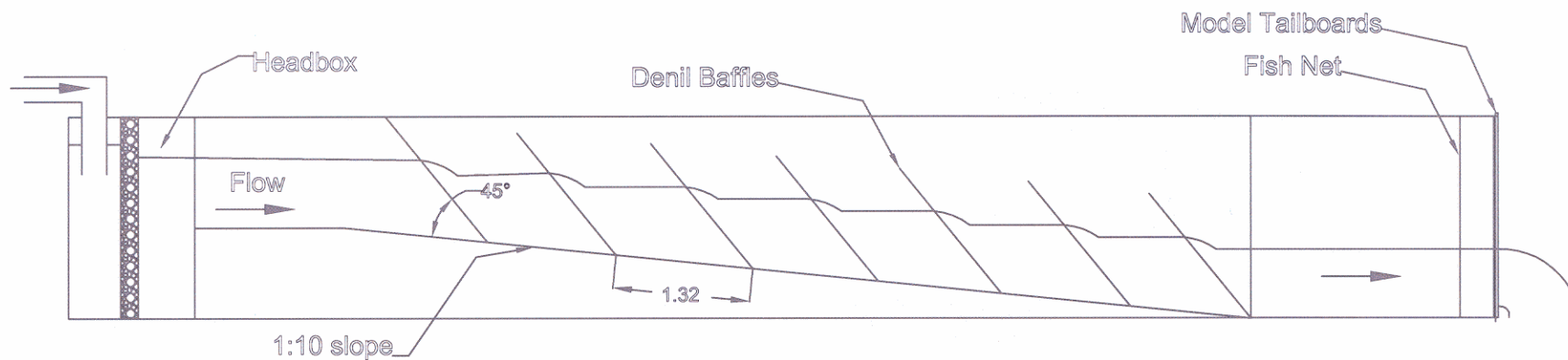
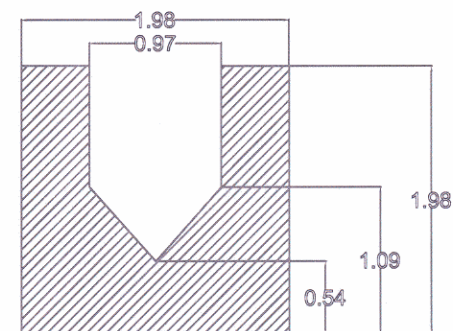


Figure 5. Vertical velocity profiles for flume channel with cobble bed flowing at target velocities of 8, 23, 38, 53 cm/sec.

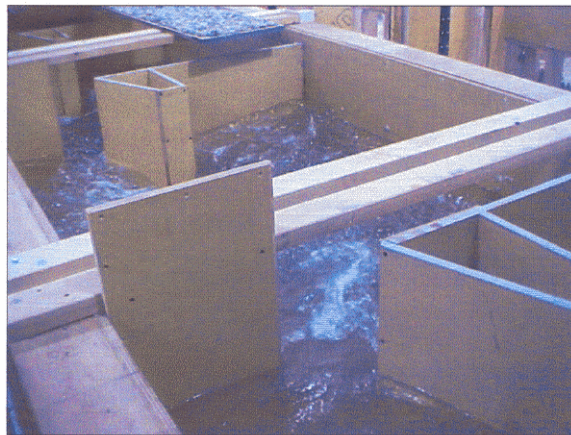
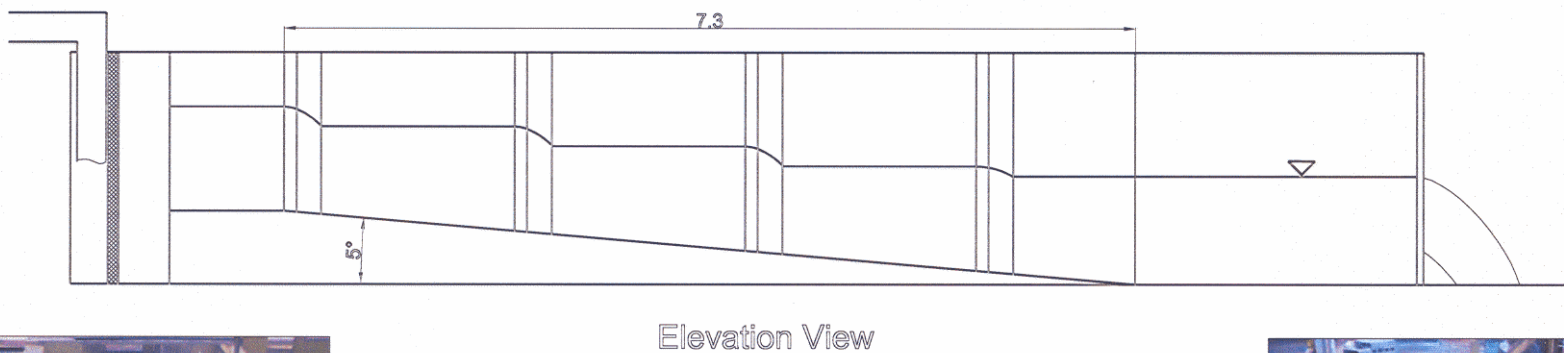
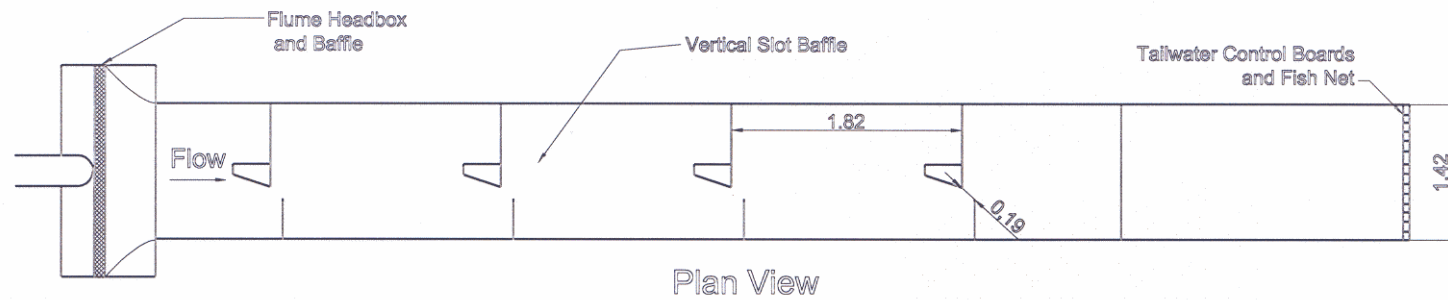


Views Looking Upstream



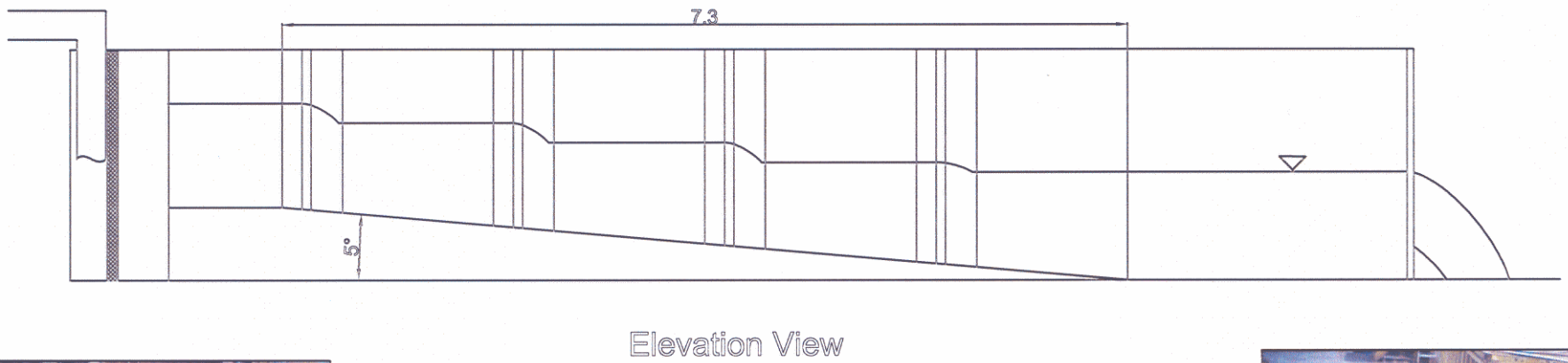
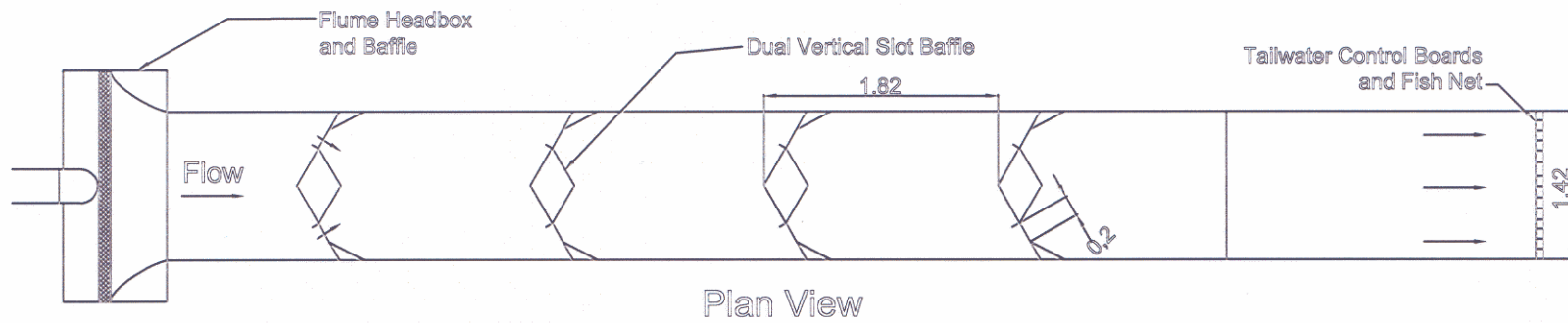
Model Baffle,(m)

Figure 6. Denil fishway used for volitional passage tests of Rio Grande silvery minnow. Dimensions in meters.

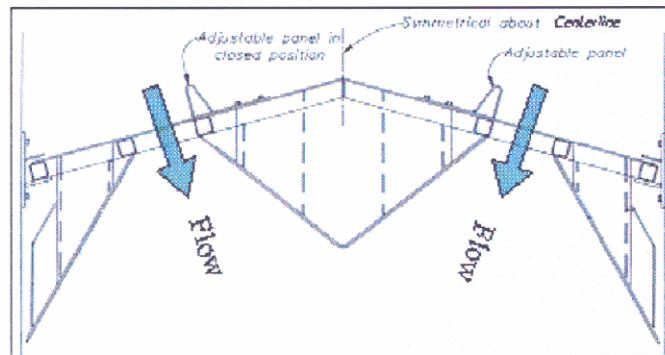


Views Looking Downstream

Figure 7. Vertical slot fishway used for volitional passage tests of Rio Grande silvery minnow. Dimensions are in meters.



View Looking Downstream



Schematic of Dual Vertical Slot Baffle



View Looking Downstream

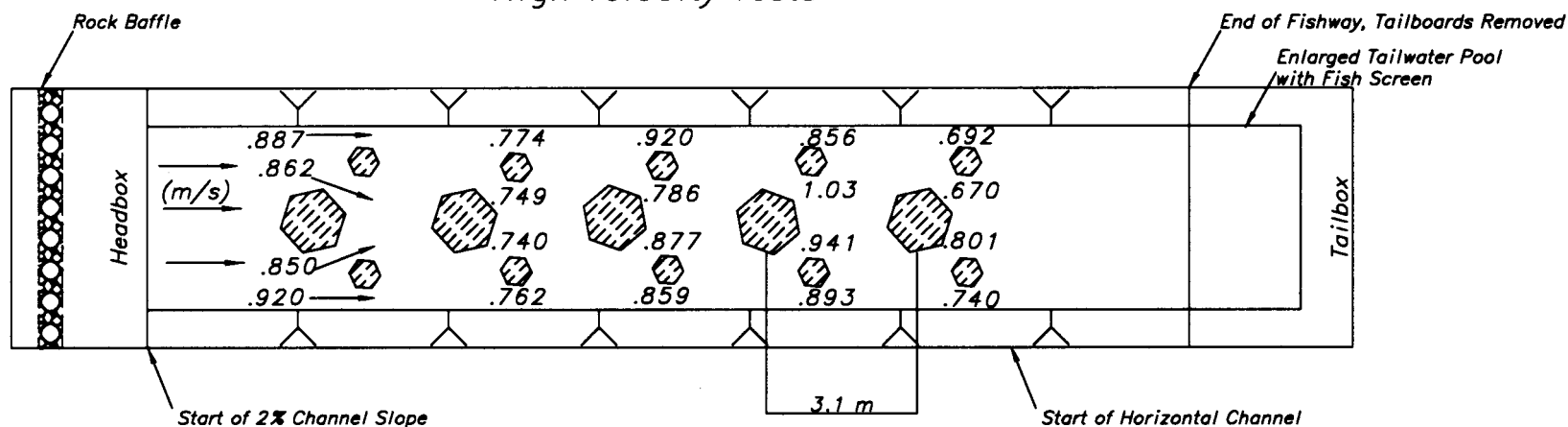
Figure 8. Dual vertical slot fishway used for volitional passage tests of Rio Grande silvery minnow. Dimensions are in meters.



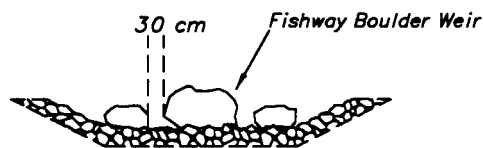
Figure 9. View of the rock model fishway looking upstream. Boulder weirs with velocities between slots are depicted in meters per second.

Rock Fishway

High Velocity Tests



Plan View



Section View

Figure 10. Plan view of rock model fishway with boulder weirs used for volitional passage tests of Rio Grande silvery minnow with high test velocity conditions. Flow is from left to right. Velocities shown were measured at mid-depth in the water column between boulders.

Rock Fishway

Low Velocity Tests

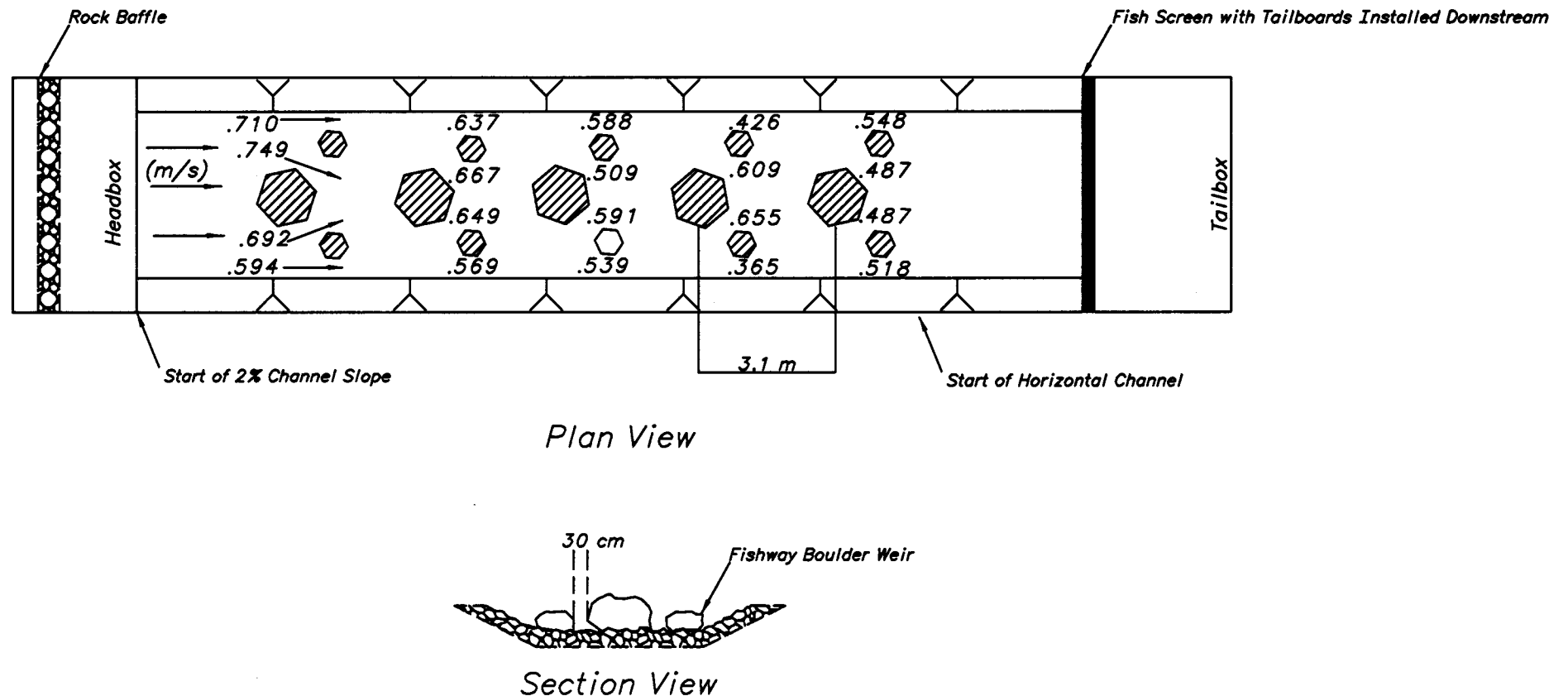


Figure 11. Plan view of rock model fishway with boulder weirs used for volitional passage tests of Rio Grande silvery minnow with low test velocity conditions. Flow is from left to right. Velocities shown were measured at mid-depth in the water column between boulders.

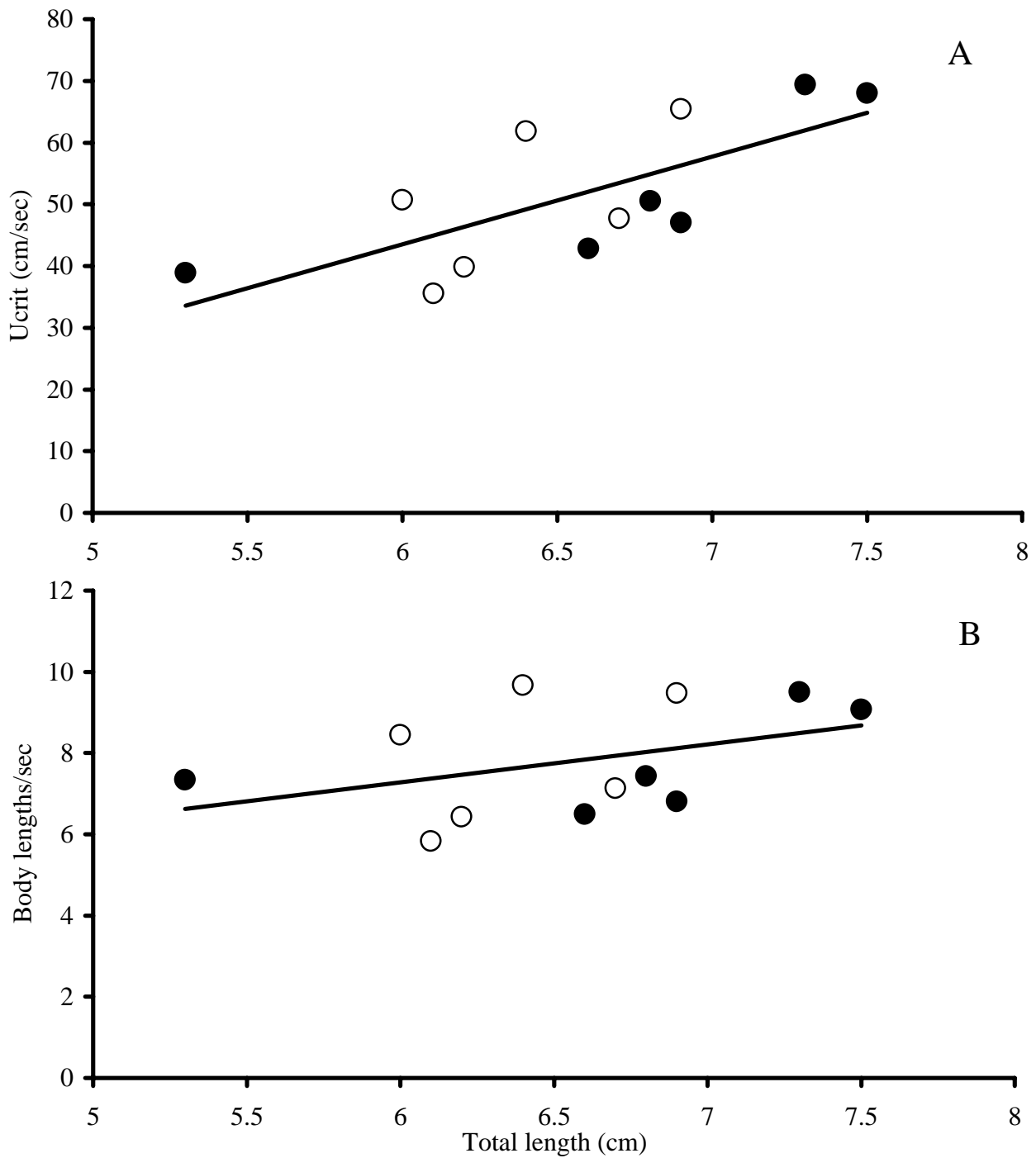


Figure 12. Critical swimming speed (U_{crit} , A) and swimming rate (body lengths/sec, B) as a function of body length for Rio Grande silvery minnows. Open symbols are for fish with short acclimation times (about 2 hrs) and filled symbols for fish with long (about 14 hrs) acclimation times.

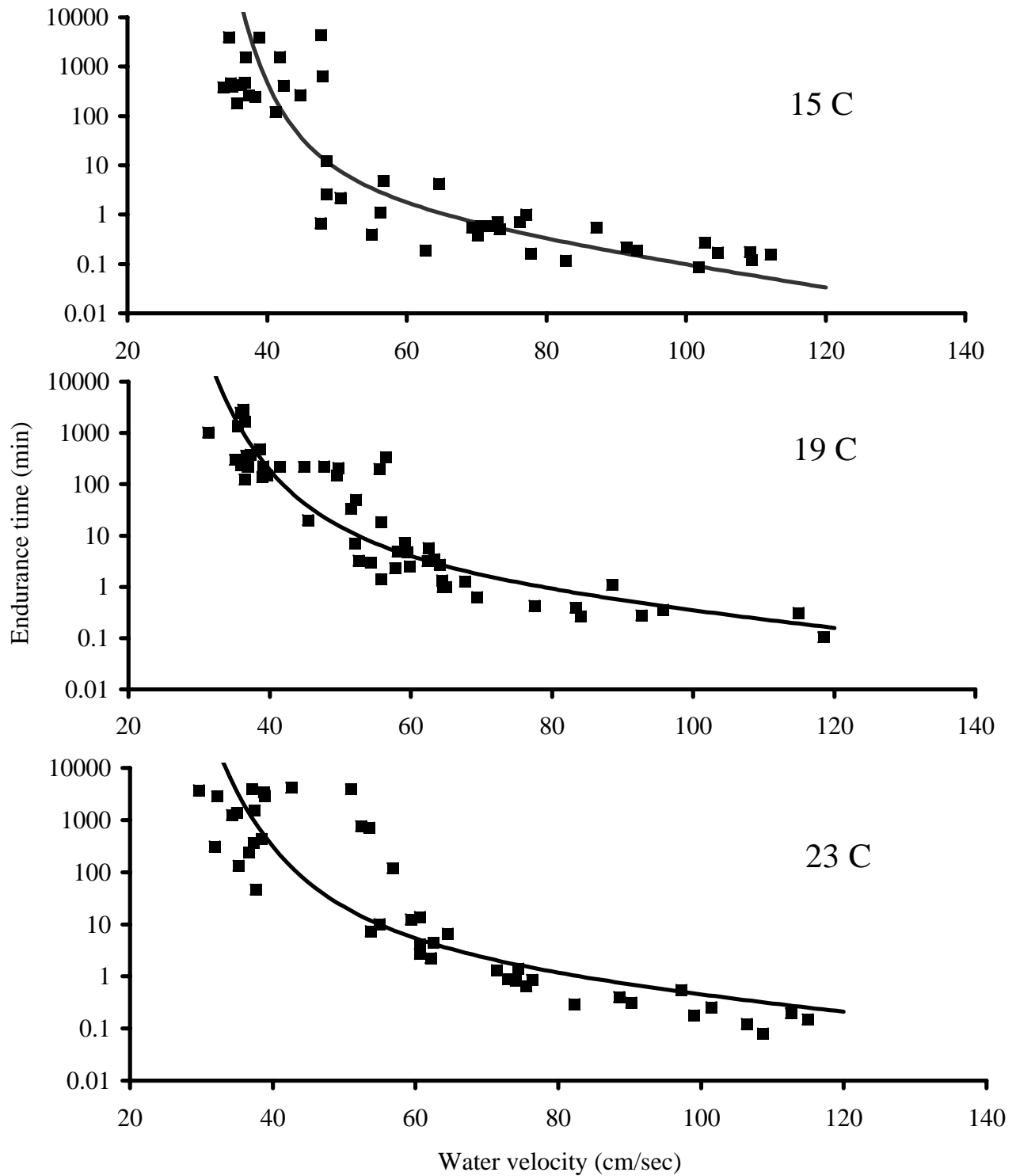


Figure 13. Non-linear regression relationships of swimming endurance of Rio Grande silvery minnow as a function of water velocity at 15, 19, and 23 C test temperatures. Symbols represent test data, solid lines are predicted swimming endurance. Regression coefficients and model fits are presented in Table 3.

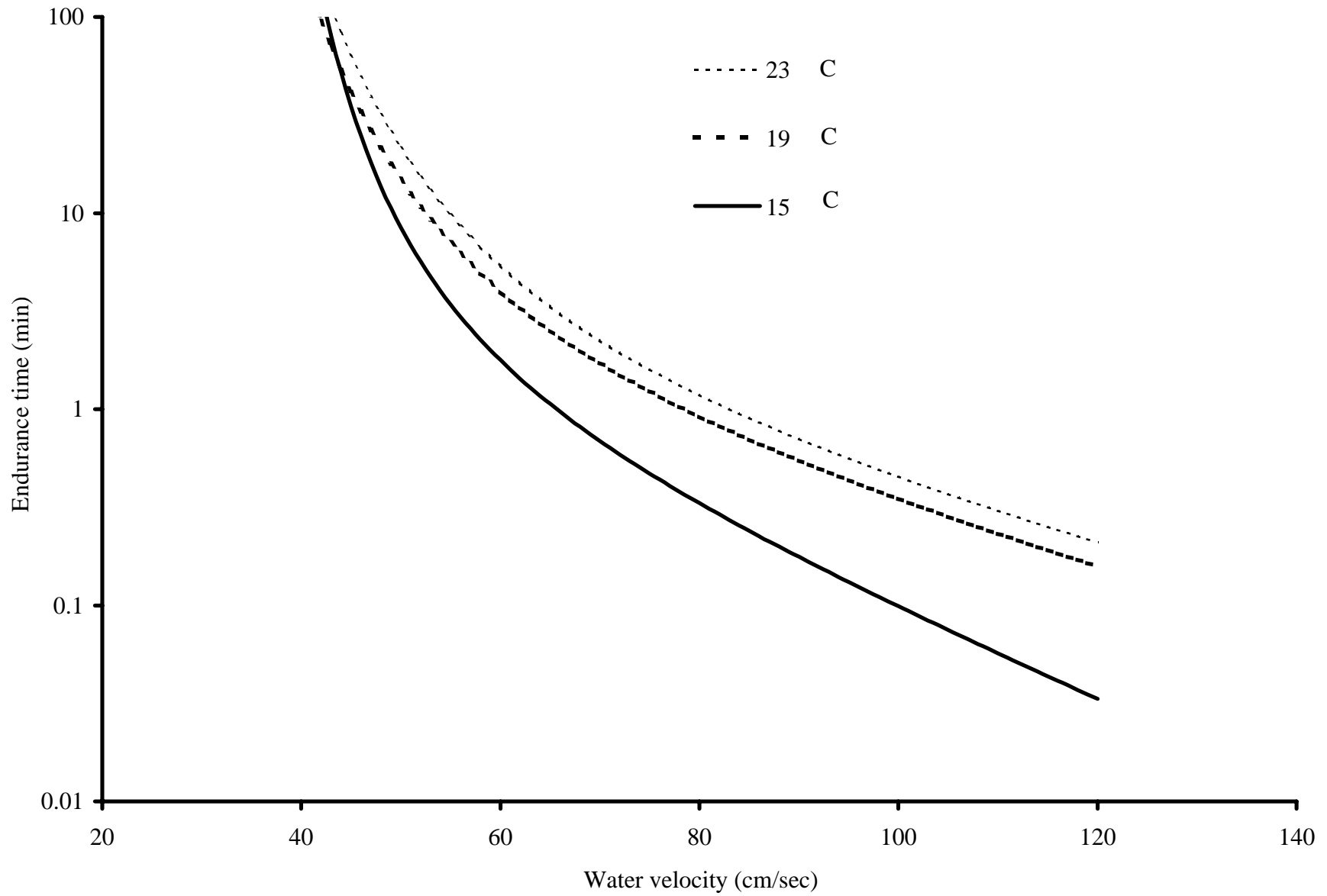


Figure 14. Predicted swimming endurance of Rio Grande silvery minnow as a function of water velocity for 15, 19, and 23 C test temperatures. Regression coefficients and model fits are presented in Table 3.

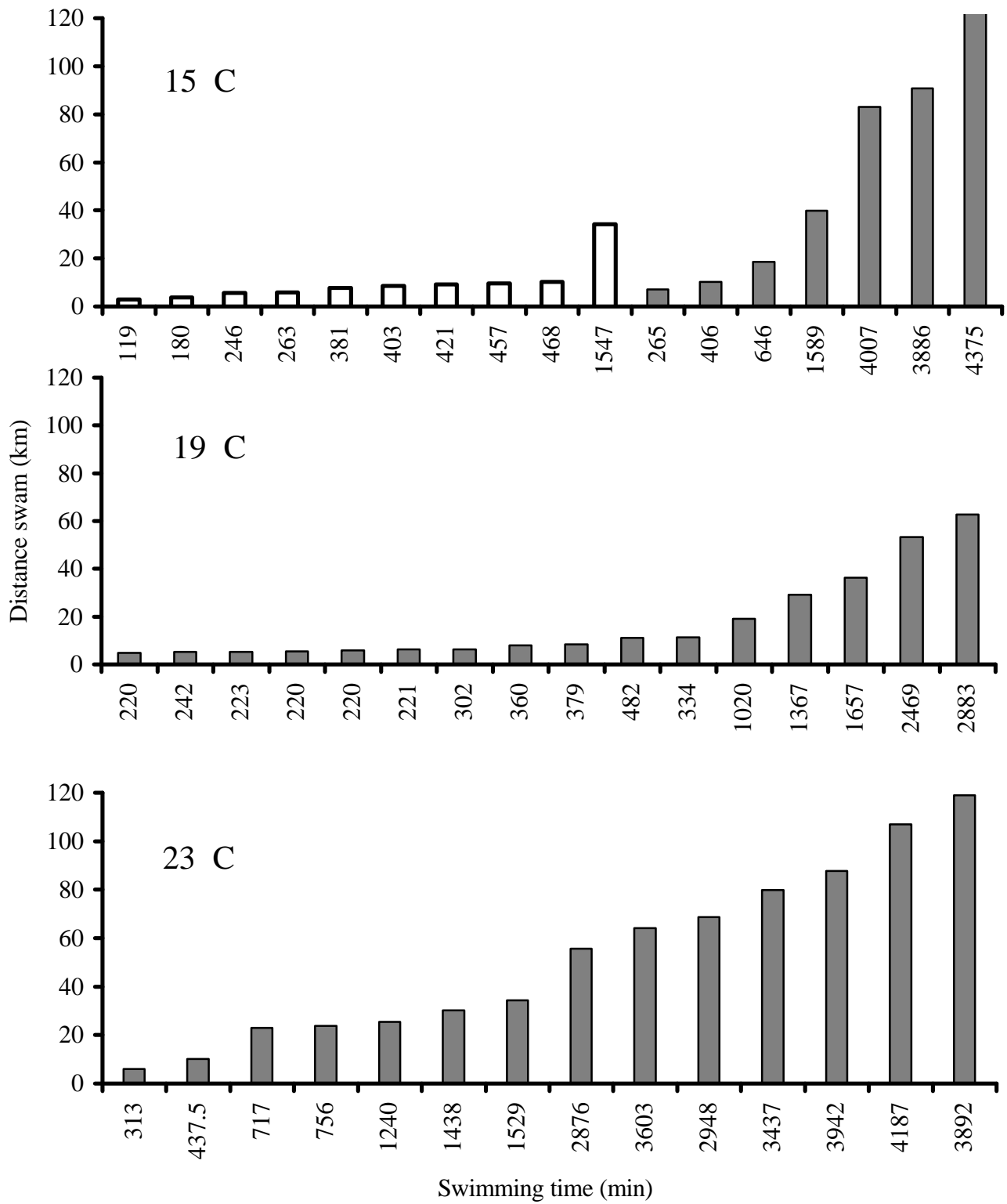


Figure 15. Long distance swimming of Rio Grande silvery minnow at 15, 19, and 23 C water temperatures. Distances were computed as the product of swimming speed in the swim chamber and duration of test. Filled bars denote wild fish, open bars are hatchery fish (15 C).

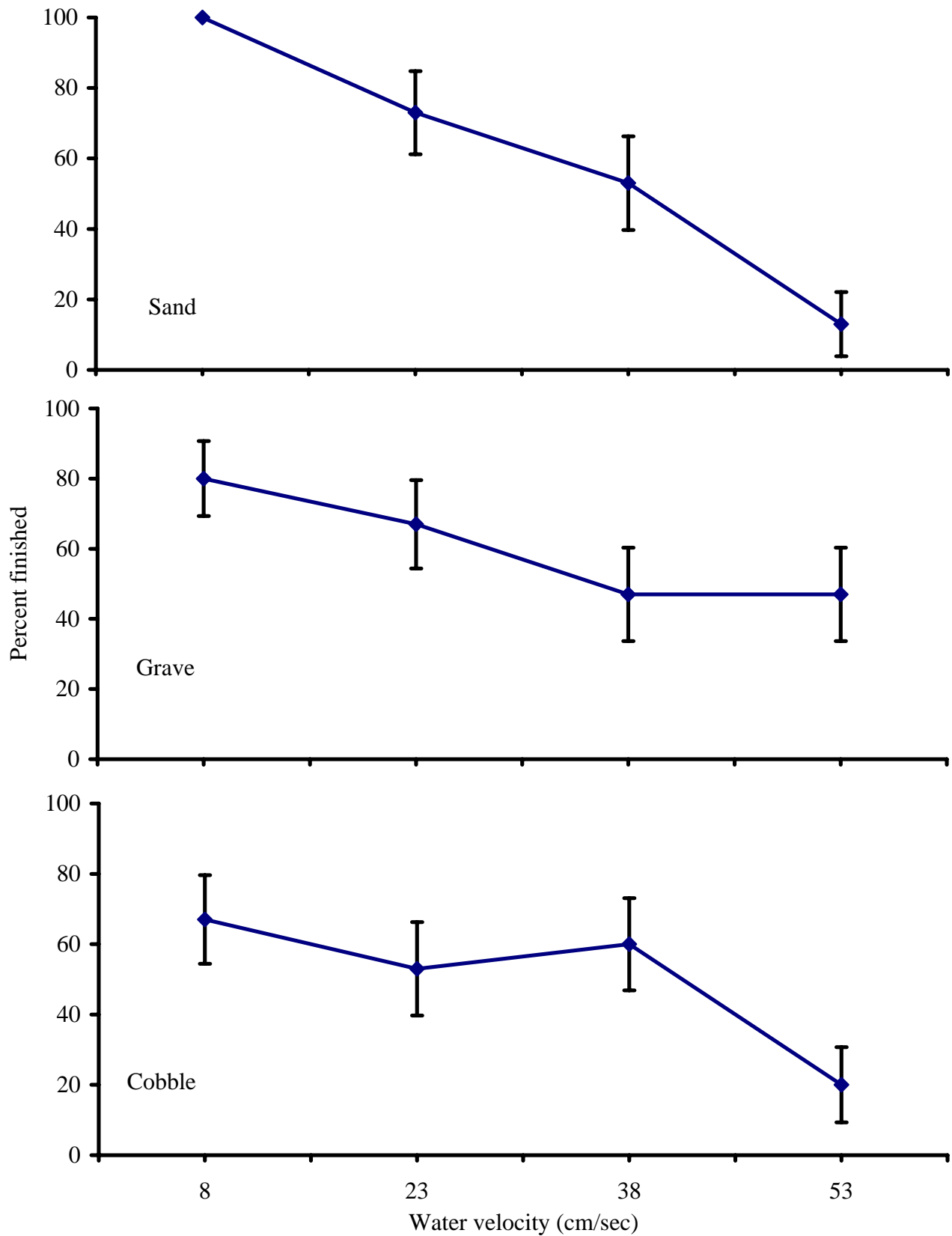


Figure 16. Proportion of Rio Grande silvery minnow that successfully swam the entire length of the experimental flume as a function of water velocity over sand, gravel, and cobble bed particles. Regression coefficients and model fits for relationships fitted are presented in Table 5. Vertical bars represent ± 1 SE.

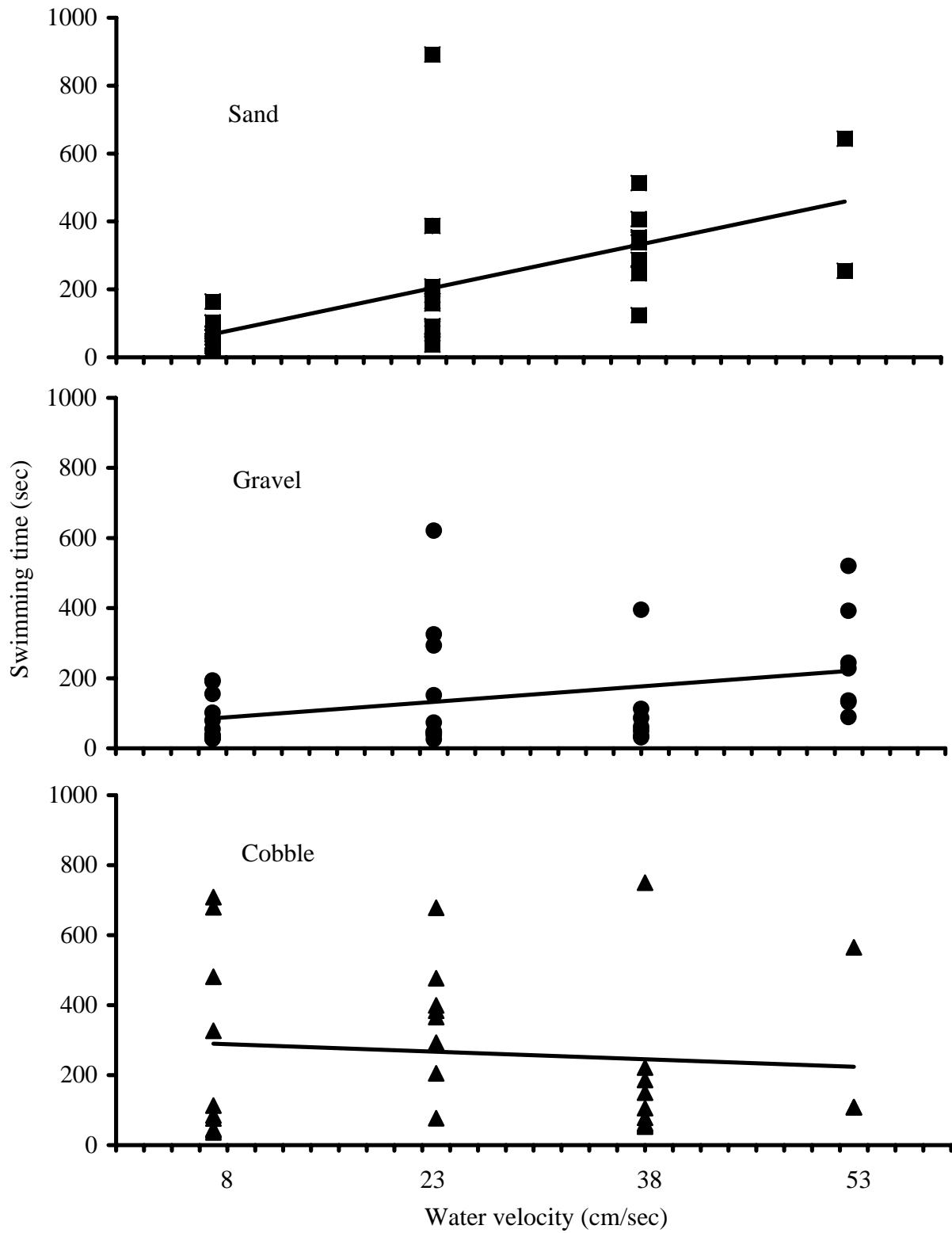


Figure 17. Relationship of swimming time to finish the entire length of the experimental flume as a function of water velocity for Rio Grande silvery minnow over sand, gravel, and cobble bed particles. Regression coefficients and model fits are presented in Table 6.

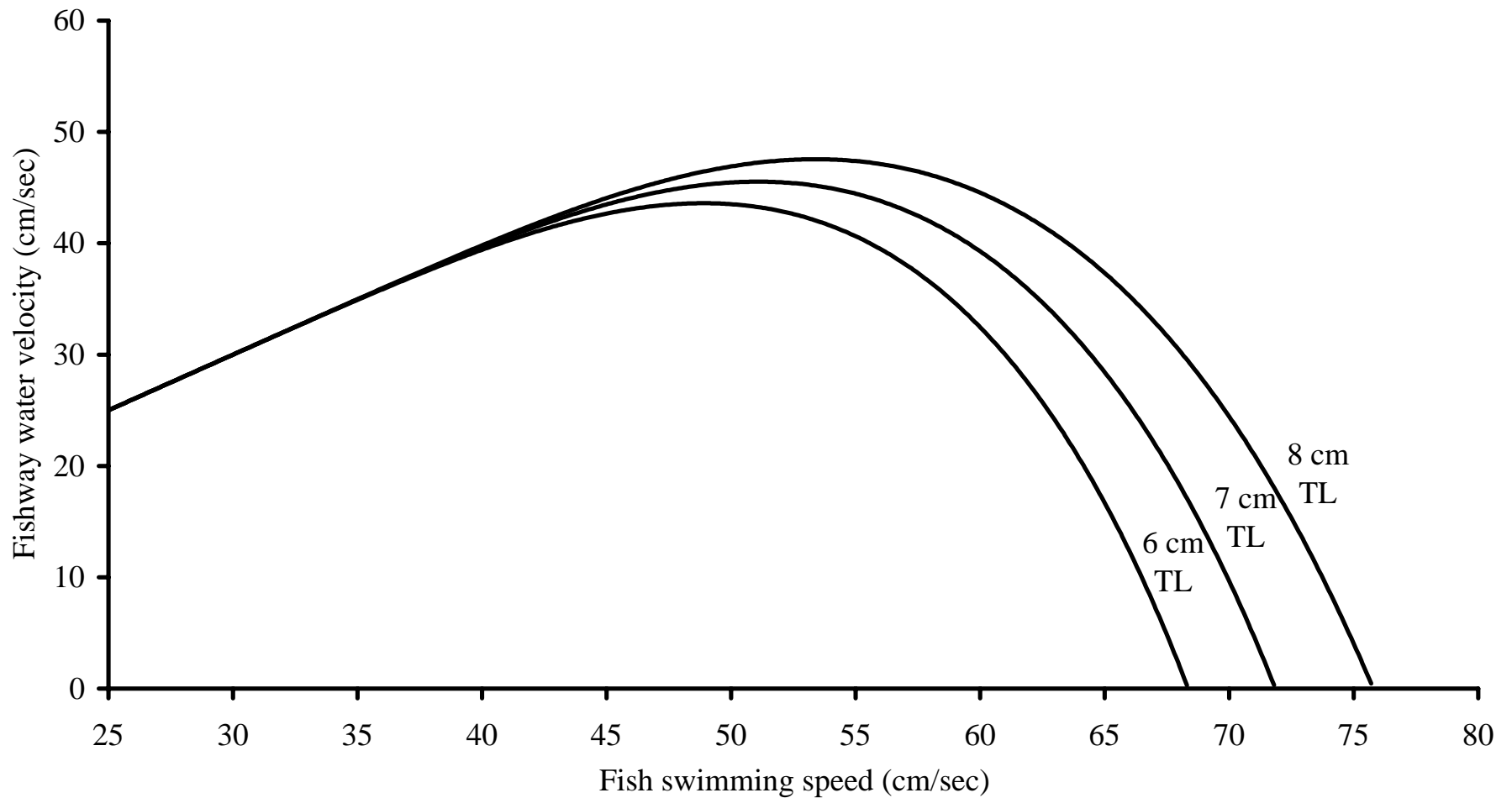


Figure 18. Relationship of swimming speed for a 6, 7, and 8 cm TL Rio Grande silvery minnow needed to pass a 50 m long fishway over a range of fishway velocities. Relationships were developed by solving equation 2 assuming a water temperature of 19 C. Any combination of fishway length, water temperature, and fish length in the range we tested can be substituted. The apex of each curve is the maximum fishway water velocity that silvery minnow can successfully negotiate.

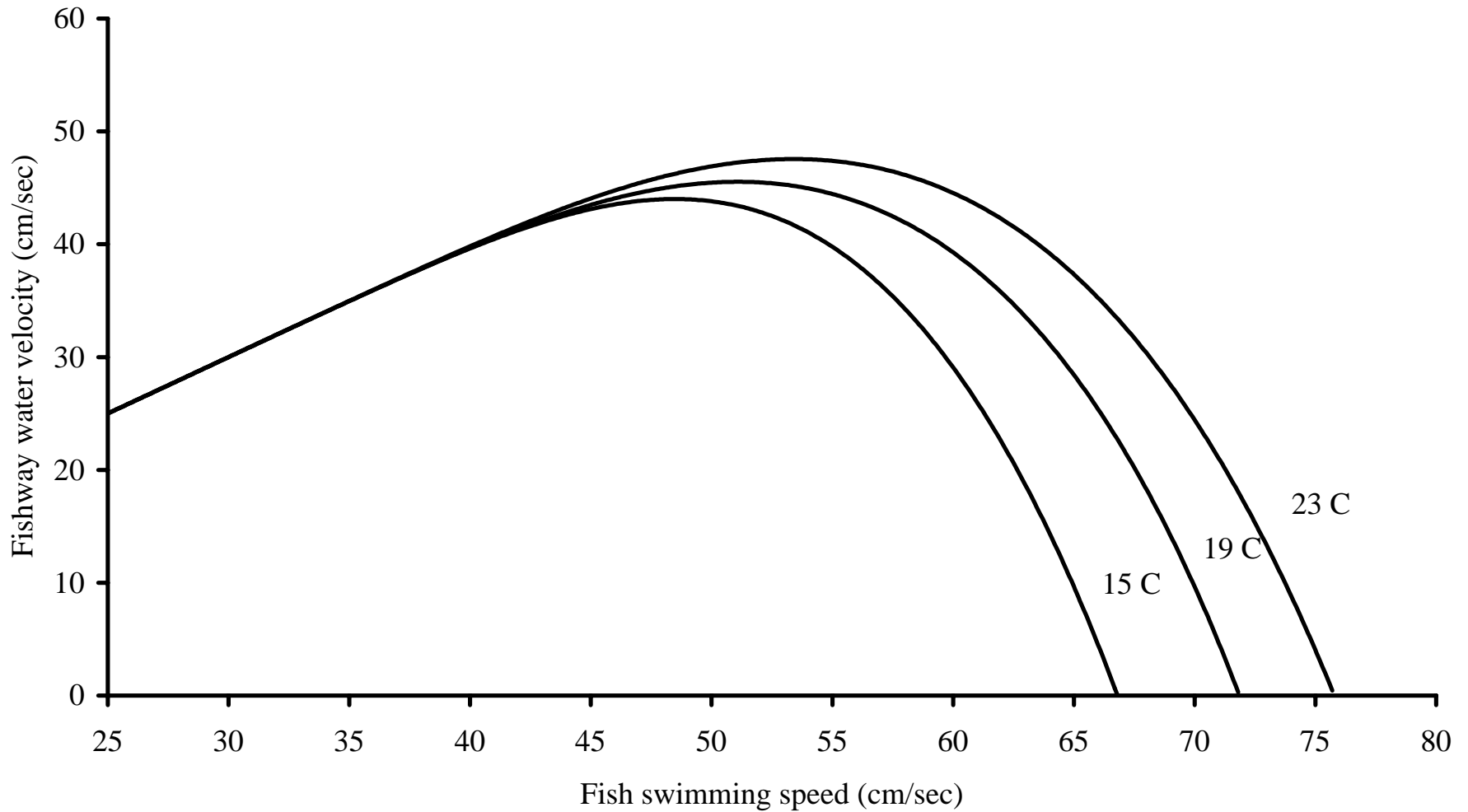


Figure 19. Relationship of swimming speed for a 7 cm TL Rio Grande silvery minnow needed to pass a 50 m long fishway over a range of fishway velocities at 15, 19, and 23 C. Relationships were developed by solving equation 2 at each temperature. Any combination of fishway length, water temperature, and fish length in the range we tested can be substituted. The apex of each curve is the maximum fishway water velocity that silvery minnow can successfully negotiate.

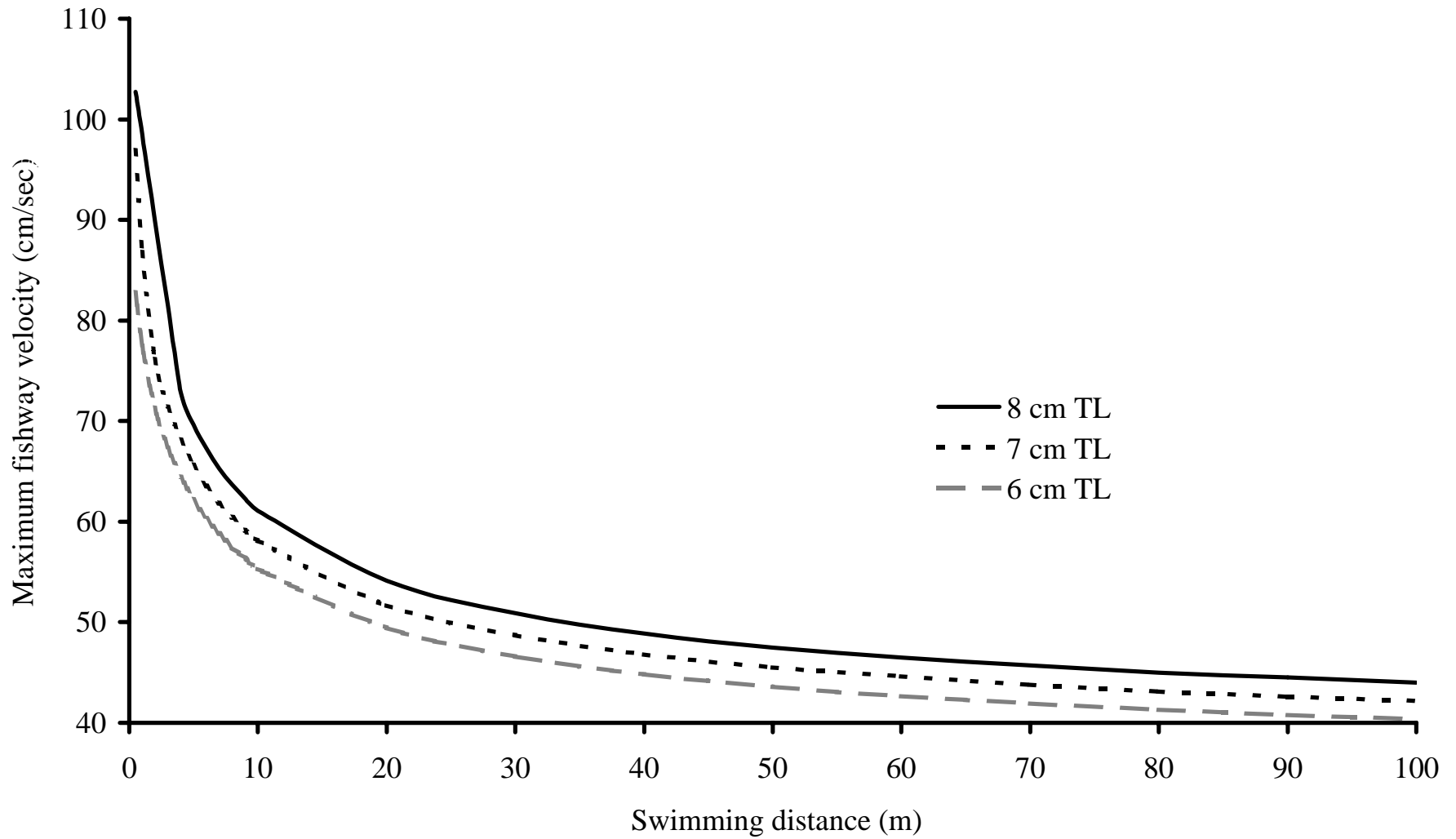


Figure 20. Relationship depicting maximum fishway flow velocity that would allow 6, 7, and 8 cm TL Rio Grande silvery minnow to pass a distance of 0.5 - 100 m. Relationships were derived by solving equation 2 at a variety of passage distances, assuming a temperature of 19 C, plotting the maximum for each distance and joining the points.