ASSESSMENT OF BEHAVIOR AND SWIMMING ABILITY OF YELLOWSTONE RIVER STURGEON FOR DESIGN OF FISH PASSAGE DEVICES

BY:

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Jan 10, 2002

Acknowledgments

We wish to thank the United States Army Corps of Engineers, Omaha District and Reclamation's Science and Technology Program for funding this project.We also thank the Montana Department of Fish, Wildlife and Parks (FWP) who collected wild fish for use in the experiments, the Bureau of Reclamation Montana Area Office for providing coordination and technical data on Intake Diversion Dam, Glendive, Montana and Reclamation's Fisheries Application Group in Denver who provided great assistance in the transport and holding of test fish.

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Background

Intake Dam was originally constructed as a rock-filled timber crib weir about 12 ft high and 700 ft long, containing 23,000 cubic yards of material. The dam raises the upstream water elevation from about 3 to 5 feet depending on river flows. Since construction, the structure has required frequent repair to maintain the needed upstream head to divert flow into the Main Canal. Heavy ice and large flood flows work to progressively move riprap material from the dam downstream. A cableway that crosses the river over the crest of the dam is used to place riprap along the dam crest when repairs are required. Over the years, large quantities of rock have been added to the dam to replace rock displaced by the river. Riprap now extends a considerable distance downstream of the dam altering the natural form of the river.

Fish population studies conducted by Montana Fish, Wildlife and Parks (Stewart, 1986, 1988, 1990, 1991) indicate the dam is a partial barrier to many species and likely a total barrier to some species. Passage of endangered pallid sturgeon is of particular importance at Intake Dam. Backes and Gardner (1994) found no pallids and significantly larger shovelnose sturgeon upstream of Intake Dam. There is little question that Intake Dam is a substantial barrier to the upstream movement of sturgeon species. However, the question remains as to the best method of attracting and passing sturgeon at Intake. The behavior of sturgeon found in the Yellowstone and Missouri River systems has been the subject of several field studies. These studies provide insight into the sturgeon's preferences of flow regime (Bramblett 1996, Backes and Gardner 1994, Erickson 1992, Peterman and Haddix 1975), channel shape (Bramblett 2001, Elser 1977, Peterman and Haddix 1975,) and channel substrate (Bramblett 1996, Backes and Gardner 1994, Baily and Cross 1954). However, when confronted by a barrier, the hydraulic conditions which are favorable to attraction and passage of sturgeon are not thoroughly understood. Little is documented about the ability of sturgeon to negotiate the combination of flow depth, velocity and turbulence.

The research study was developed in response to a request for proposals (RFP) issued by the US Army Corps of Engineers (COE) via electronic mail on May 16, 2001. The study was designed to investigate the interaction between flow conditions and the behavior and swimming ability of pallid sturgeon for use in the design of fish passage structures. Wild adult shovelnose sturgeon from the Yellowstone River were used as a surrogate species as recommended in the RFP. Results of habitat use studies conducted by Bramblett (1996) comparing pallid and shovelnose sturgeon were used in experimental design and evaluation of test data.

Study Participants and Facilities

The study was conducted at Reclamation's Water Resources Research Laboratory (WRRL) in Denver, Colorado. Montana State University (MSU) and Reclamation jointly participated in the research study. Montana State University provide the lead for permitting, biological testing and assessment. Reclamation provided the lead for designing and constructing test apparatus at WRRL and conducting hydraulic evaluations of test conditions.

Fish Collection and Handling

Adult shovelnose sturgeon used in the study were collected from the Yellowstone River by Montana Fish, Wildlife and Parks (MFWP) personnel. Twenty six shovelnose sturgeon were collected July 17, 2001 and 14 October 16, 2001. Dr. Dave Erdahl at the USFWS Bozeman Fish Technology Center and MFWP were consulted on captive handling, transport and maintenance of shovelnose sturgeon. Both groups of fish were transported to Reclamation's Water Resources Research Laboratory (WRRL) in Denver, Colorado shortly after being collected. Fisheries biologist from Reclamation's Fisheries Application Group in Denver transported the fish by vehicle in aerated tanks. The fish were iced down during transport and arrived in Denver in good condition. Upon arrival water temperature was tempered and fish were placed in two 9 foot diameter by 2.5 foot deep circular plastic tanks at WRRL and given a mild salt treatment (Figure 1). Water was continuously circulated through the fish holding tanks from the laboratory's water supply reservoir located beneath the laboratory floor. Water quality within the WRRL water supply reservoir is maintained by an ozonation system. No additional water treatment was required. The water temperature of the supply reservoir was 64?F ± 2 ?throughout the testing. These water temperatures were typical of Yellowstone River temperatures during spawning (Bramblett 1996) and considered adequate for all tests. Water temperature in the fish holding tanks was cooled to 62?F based on recommendations offered by Dr. Erdahl. His experience with holding Yellowstone River sturgeon for extended periods has shown fish survival is best at water temperatures about 60?F. Fish were fed both commercial trout diet and live night crawlers.

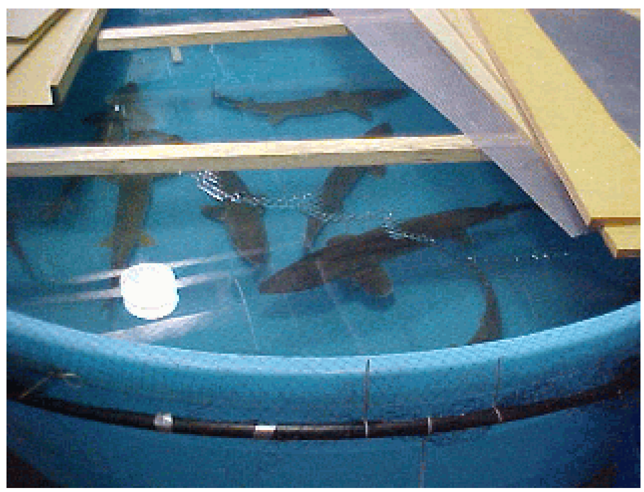


Figure 1 - View of sturgeon in circular holding tank.

Test sturgeon in group 1 ranged in fork length from 25.2 inches (the 24.6 inch fish had a damaged tail and was not used) to 35.8 inches (mean 31.8) (Figure 2) and weighed 3.1 to 10.6 pounds (mean 6.7) (Figure 3). Group 2 fish ranged in fork length from 28.5 inches to 31.5 inches (mean 30.4)

Study Scope

The study was divided into two experimental phases. The first phase focused on identifying the behavior of sturgeon exposed to a combination of flow depth, velocity, and turbulence. These parameters are important in the design of effective fishway attraction and passage conditions. After preliminary testing, we determined that the series of depths tested had no observable influence on sturgeon behavior and depth was eliminated as a test veriable (depth remained constant). The second phase observed the response of shovelnose sturgeon to three types of fishways: a standard vertical slot baffled fishway, a duel-vertical slot baffled fishway and a rock channel with boulder weirs. We planned to conduct both day and night tests, but since sturgeon movement in preliminary tests was good during light periods, night tests were not conducted.

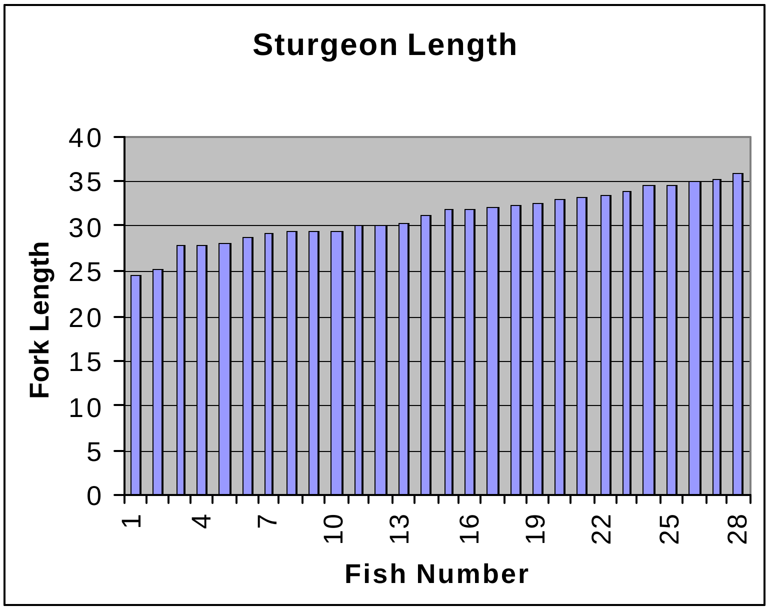


Figure 2 - Fork length of shovelnose sturgeon in test group 1.

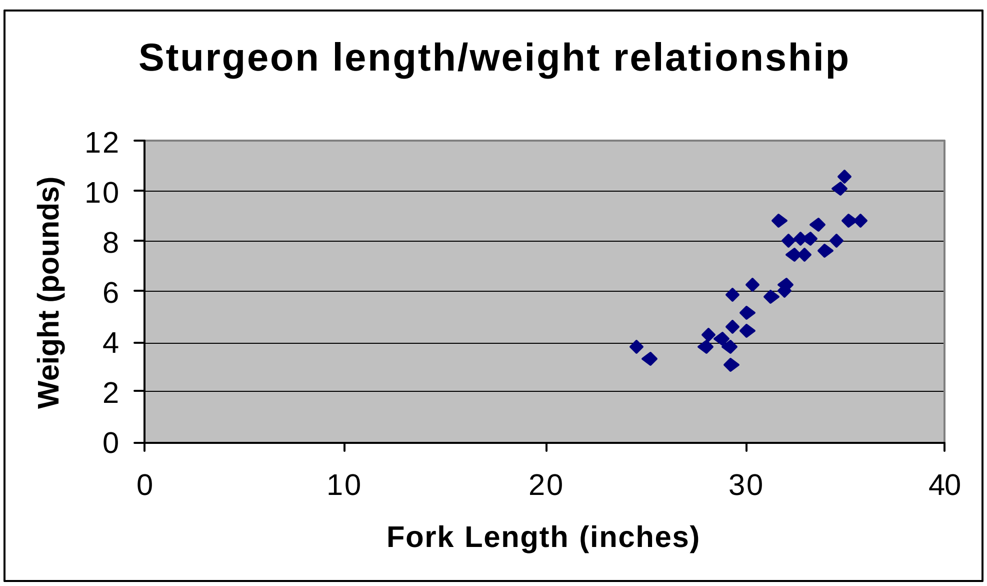


Figure 3 - Weight versus fork length of shovelnose sturgeon in test group 1.

Sturgeon Response to Flow Velocity, Channel Bed Roughness and Flow Turbulence

Flow Velocity and Bed Roughness

Experimental Apparatus

Two flumes were used during velocity and substrate tests. A 3 ft wide by 30 ft long by 5 ft deep horizontal flume was used to observe fish behavior and movement for tests of average flow velocity up to 4.0 ft/s (Figure 4). A second adjustable slope flume was used to test fish at velocities above 4.0 ft/s. The sloping flume is 3 ft wide by 60 ft long by 1.5 ft deep (Figure 5). The flume's slope can be adjusted from -0.5 degrees to 8 degrees. Both flumes have glass walls allowing visual observation of fish behavior.

Test Procedure

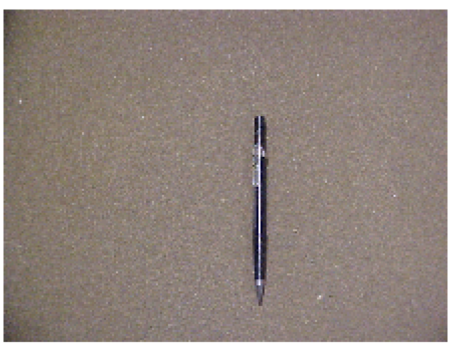
Bed roughness and velocity ranges were selected based on field data of sturgeon habitat preferences summarized in Table 1. Tests were conducted using four bed roughnesses at nine flow velocities (Table 2). Bed roughnesses tested were fine sand, course sand, gravel and cobble (Figure 6). Tests of sand and gravel beds were conducted by placing sheets of marine plywood coated with each roughness on the flume floor. A cobble bed was created by placing a layer of tightly packed cobbles within the flume.

Table 1 - Summary of shovelnose and pallid sturgeon habitat preferences identified in available literature.

Study Author	Depth		Velocity		Substrate	
	Pallid	Shovelnose	Pallid	Shovelnose	Pallid	Shovelnose
Bramblett, 1996, Yellowstone River	2 to 23 ft	3 to 29 ft	0.4 to 4.33 ft/s	0.1 to 6.0 ft/s	>90 % sand bed, <5% gravel	26 % sand, 69% gravel
Erickson, 1992, Lake Sharpe, SD.	13 to 20 ft	NA	0 to 2.4 ft/s	NA	All	NA
Schmulbach et al., 1982 experimental data	NA	NA	NA	2.5 ft/s ± 1.5 ft/s (critical velocity)	NA	NA
Peterman and Haddix, 1975, Tongue River	NA	1.4 to 3 ft	NA	NA	NA	NA

Figure 4 - View of 3 ft wide by 30 ft long by 5 ft deep horizontal flume.

Figure 5 - View looking downstream in the 3 ft wide by 60 ft long by 1.5 ft deep adjustable slope flume.



Fine Sand Bed Roughness

Course Sand Bed Roughness

Gravel Bed Roughness

Cobble Bed Roughness

Figure 6 - Photographs of bed roughness materials used for sturgeon swimming tests.

At the initiation of a test, water velocity and depth were set at 0.8 ft/s and 18 inches, respectively. Two sturgeon were netted from the holding tank based on size (one longer than the other) or color (light /dark) so fish-specific observations could be made. Fish were placed in a large water-filled cooler and lifted by overhead crane (30 ft flume) or transported by dolly (adjustable slope flume) and released into the bottom of the flume. Observations of fish movement were recorded throughout 20 or 30 minute trials. At the end of a trial, velocity was increased by increasing discharge while keeping depth constant. Average velocities tested were 0.8 ft/s, 1.2 ft/s, 1.6 ft/s, 2.0 ft/s, 2.5 ft/s, 3.0 ft/s, 3.5 ft/s, 4.0 ft/s and 6.0 ft/s (adjustable slope flume). At the end of a test series or when a fish became impinged on the bottom screen, fish were removed and fork length measured. Handling, was kept to a minum to minimize stress. To avoid reusing the fish until all fish had been tested, each sturgeon was marked with a numbered strip of duck tape loosely secured around the caudal peduncle.

Table 2. Test variables - Bed roughness and flow velocity

Fine Sand, <0.01 in diameter
Course Sand, 0.1 in- 0.25 in diameter
Gravel, 0.5 in - 1.0 in diameter
Cobble, 2 in - 8 in diameter

?

Average Velocity, ft/s	Depth, ft
0.8	1.5
1.6	1.5
2.0	1.5
2.5	1.5
3.0	1.5
3.5	1.5
4.0	1.5
6.0	0.7

Adjustable Slope Flume Tests - Bramblett (1996) documented sturgeon in current velocities up to about 6.0 ft/s. Average velocities greater than 4.0 ft/s were not attainable in the 30 foot flume. Therefore, a similar series of tests were conducted in the adjustable slope flume to observe behavior and movement at velocities in the range of 6 to 6.5 ft/s. Bottom substrates tested were smooth bed, coarse sand, gravel and cobble. A smooth bed (plywood flume floor) was substituted for the fine sand bed substrate during the sloping flume tests to observe behavior on a channel bed similar in roughness to a trowel finished concrete surface. The downstream one-third of the channel length was backwatered to provide a method of exposing the fish to an increasing velocity with time. Velocity at the downstream end of the flume was increased in steps similar to tests conducted in the 30 ft flume. Upstream of the backwater zone, flow approached normal depth. It was desired to have a similar velocity at mid-depth for each bed roughness. To achieve similar velocities, flume slope was varied between tests of different bed roughness (Figure 7). A temporary net was inserted 20 feet up from the bottom of the flume to hold fish in the backwater zone as velocity was stepped up (see figure 5). This allowed the flume slope to be held constant during trails at a fixed bed roughness and did not require fish to be moved down for each velocity trial. Test duration was a maximum of 30 minutes but shorter if both fish had moved to the temporary net.

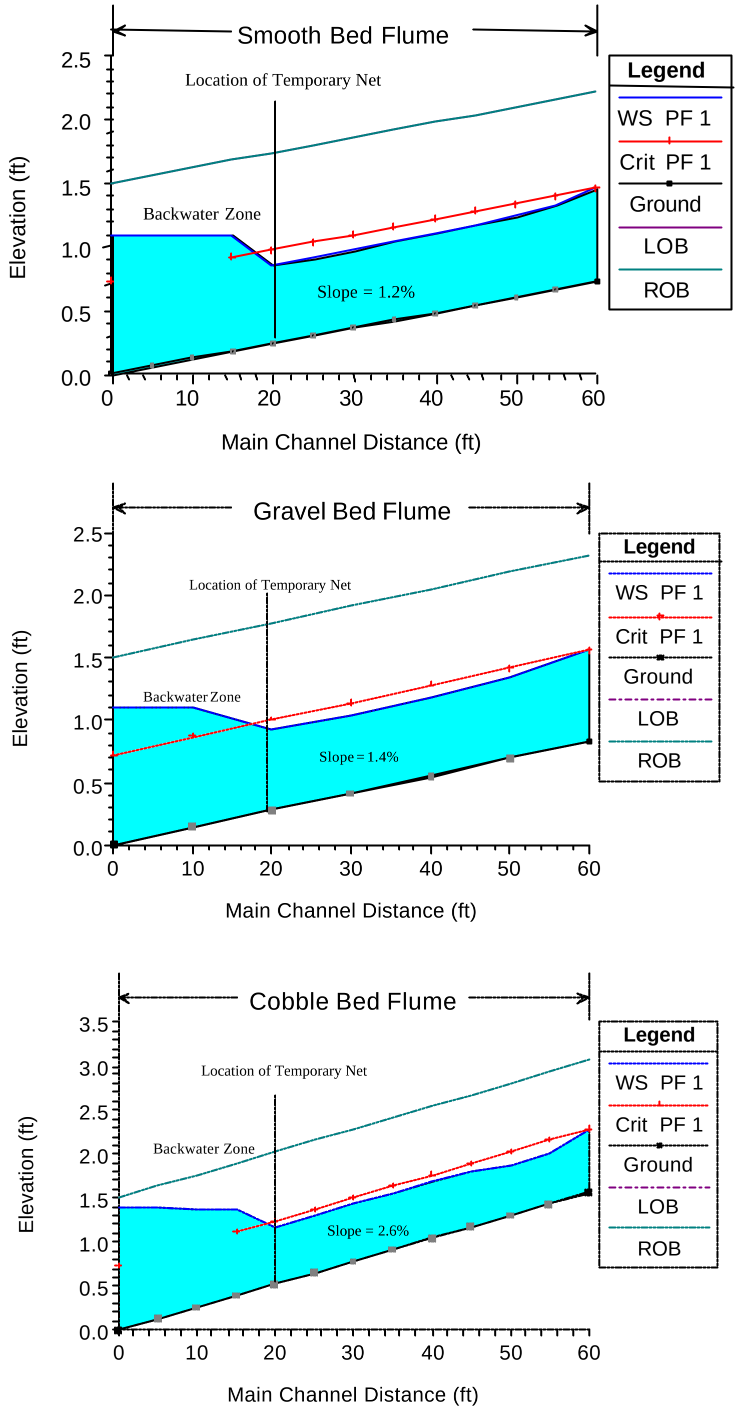


Figure 7 - Watersurface profiles predicted for sloping flume tests using smooth, gravel and cobble bed roughness, HEC-RAS numerical model.

Velocity and Bed Roughness Test Results

Thirty-Foot-Flume Tests - As part of our examination of the influence of velocity and substrate type on sturgeon behavior, we conducted 6 tests consisting of 46 trials in the 30 foot flume. Each test evaluated the behavior of two sturgeon at seven or eight average velocities (trials) ranging from 0.8 ft/s to 4.0 ft/s, and one of four substrate types (fine sand, coarse sand, gravel, and cobble, see Table 2). Vertical velocity profiles are presented in Figures 8 to15 showing the average downstream velocity component (V_x) and the fluctuation of the vertical velocity component expressed as an root-mean-squared-value (V_z rms). Velocity is plotted as a function of distance above the bed. Due to the high irregularity of the gravel and cobble beds a virtual zero bed datum was established based on near bed velocity. The virtual datum was established as the lowest point of continuously positive downstream flow. The velocity profiles show a sharp velocity reduction of V_x for increasing bed roughness. The velocity reduction (boundary layer) is most apparent in the first 4 inches above the bed. In the near bed zone, V_z rms increases with bed roughness. The increase is most pronounced for the cobble bed where the maximum V_z rms values were found to be about 10 percent of V_x max.

Sturgeon successfully negotiated the range of velocities tested, over all substrates. Success was defined as moving from the bottom of the flume to the top within a 30 minute period. Although there were small differences in success associated with substrate type, with cobble being the poorest, small sample size and high individual variation precluded conclusive determination of the influence of substrate. However, pattern of success related to velocity was consistent among substrates. The lowest overall percent success occurred at 0.8 ft/s (67%), increasing to 83% at 1.2 ft/s and 1.6 ft/s, and to 100% at velocities of 2.0 ft/s, 2.5 ft/s, and 3.0 ft/s (Table 3). Success dropped to 92% and 87% at 3.5 ft/s and 4.0 ft/s, respectively. This indicates that attraction velocity becomes strong at 2.0 ft/s and remains high up to 4.0 ft/s.

General fish behavior associated with substrate was also similar among types and movement patterns related to velocity. Sturgeon moved most at low and high velocities (Table 4). At low velocities, fish were less oriented to flow and milled around, moving up and down channel. Up and down movement averaged 4.08 and 4.90 per fish at 0.8 ft/s and 1.2 ft/s, respectively; and movement was throughout the channel. Seventy-six and 18% percent of down-channel movement was head first, suggesting low orientation to flow. Total movement was less at velocities between 1.6 ft/s and 3.5 ft/s and all down-channel movement was tail first, suggesting strong flow orientation. At high velocities, up and down movement increased, with an average total up and down movement of 4.17 trips at 3.5 ft/s and 4.38 trips at 4 ft/s. However, most movement at high velocities was near the upper end of the channel and all down-channel movement was tail first, indicating high orientation to flow. Average time required to first reach the top was slowest at 0.8 ft/s (8.8 minutes) and fastest at 4.0 ft/s (0.8 minutes).

Table 3. Comparison of the number of sturgeon successfully negotiating the 30 foot flume (number to top / number tested) at eight velocities (0.8 - 4.0 ft/s) tested with three substrate types (12 fish), two vertical barrier widths (8 fish), and four horizontal baffle heights (14 fish).

				VELOCITY				
				SUBSTRATE TESTS				
Velocity	0.8	1.2	1.6	2.0	2.5	3.0	3.5	4.0
Sand	3 / 4	3 / 4	3 / 4	4 / 4	4 / 4	4 / 4	4 / 4	-
Gravel	3 / 4	4 / 4	4 / 4	4 / 4	4 / 4	4 / 4	4 / 4	4 / 4
Cobble	2 / 4	3 / 4	3 / 4	4 / 4	4 / 4	4 / 4	3 / 4	3 / 4
Total	8 / 12	10 / 12	10 / 12	12 / 12	12 / 12	12 / 12	11 / 12	7 / 8
%	67	83	83	100	100	100	92	87
				VERTICAL BAFFLE TESTS				
Baffle Width								
15.5 inch	1 / 2	-	2 / 4	1 / 2	3 / 3	3 / 3	2 / 3	2 / 3
22.5 inch	-	-	3 / 4	0 / 2	2 / 4	-	0 / 2	1 / 3
Total	1 / 2	-	5 / 8	1 / 4	5 / 7	3 / 3	2 / 5	3 / 6
%	50	-	63	25	71	100	40	50
				WEIR BAFFLE TESTS				
Baffle Height								
3 inch	1 / 4	2 / 4	3 / 4	4 / 4	4 / 4	4 / 4	2 / 2	2 / 2
6 inch	1 / 4	2 / 4	4 / 4	3 / 4	3 / 4	3 / 4	3 / 3	3 / 3
12 inch	0 / 4	3 / 4	2 / 4	3 / 4	3 / 4	1 / 3	1 / 1	1 / 1
21 inch	0 / 2	1 / 2	0 / 2	0 / 2	0 / 2	1 / 2	0 / 2	0 / 2
Total	2 / 14	8 / 14	9 / 14	10 / 14	10 / 14	9 / 13	6 / 8	6 / 8
%	14	57	64	71	71	69	75	75
Overall Total	11 / 28	18 /26	24 / 34	23 / 30	27 / 33	24 / 28	19 / 25	16 / 22
Overall %	39	69	71	77	82	86	76	73

Table 4. Average movement of 12 shovelnose sturgeon in the 30 foot flume at velocities ranging from 0.8 ft/s to 4.0 ft/s, over sand, gravel and cobble substrate.

Velocity, (ft/s)	Time to Top (minutes)	Number of Times Fish Moved to Top	Number of Times Fish Moved Up	Number of Times Fish Moved Down	Total Movement U+D	Moved Downstream Head First (Percent)
0.8	8.8	1.00	2.67	1.42	4.08	76
1.2	3.2	1.10	2.78	2.12	4.90	18
1.6	2.3	0.75	1.42	1.83	3.25	0
2.0	2.0	1.08	1.92	1.67	3.59	0
2.5	2.2	1.17	1.83	1.75	3.58	0
3.0	2.2	1.08	1.25	1.50	2.75	0
3.5	2.8	1.67	2.00	2.17	4.17	0
4.0	0.8	1.38	2.50	1.88	4.38	0

Sloping Flume Tests - We tested a maximum of five velocity ranges for each substrate type, for a total of 61 trials (Table 5). Because the flume was tilted, within the backwater zone (below the removable net), depth decreased and flow velocity increased moving up the flume. For a distance of about 20 ft upstream of the net location flow conditions were nearly constant (? fully developed flow) for coarse sand, gravel and cobble substrates. Between the upstream end of the flume and the onset of fully developed flow, was a length of channel in which flow accelerated as it moved down the flume. Flow in the smooth bed flume accelerated down the entire flume upstream of the backwater zone. Fish were allowed to move to the top of the flume during the tests of highest velocity. Velocity was measured at the downstream end of the flume, at the temporary net and 20 ft upstream of the temporary net. These velocities are denoted herein by the subscripts *d* (downstream), *n* (net) and *u* (upstream). Vertical velocity profiles for each substrate measured 40 ft upstream of the flume's downstream end are given in Figure 16. In the smooth channel, average flow velocity 20 ft upstream of the temporary net was similar to the roughened bed channels, however the average velocity increased to about 6.8 ft/s at entry to the backwater zone.

At lower velocity ranges, fish movement and behavior was similar to that observed at comparable velocities in the 30 foot flume. At the 0.8_d -1.1_n ft/s velocity range fish milled around in the channel and did not actively try to pass beyond the removable net. As velocities were increased, sturgeon became more flow oriented and when down-channel movement occurred it was primarily tail first compared to a mix of head first and tail first movement at the low velocities. Also, as velocity increased fish spent considerable time nosing the removable net in an attempt to pass.

Overall movement success was 57 % at the 0.8_d -1.1_n ft/s velocity test, increasing to 70% and 81 % at the 1.6_d -2.5_n ft/s and 2.0_d -3.3_n ft/s velocity tests, respectively, then declining to 47% at the 2.2_n-6.0_u ft/s velocity tests (Table 5). Movement success was best over smooth bottom (60-90%), followed by coarse sand (50-66%), gravel (33-80%), and cobble (25-50%). When the net was removed for the 2.2_n -6.0_u ft/s velocity test, fish holding at the net usually moved up immediately and reached the top in less than 6 minutes. Unlike the "crawling" behavior at lower velocities, fish actively swam at the high velocity. Although some fish sprinted the entire distance without stopping, most moved up in three or four spirts, resting apparently effortlessly in the high velocity flow. Maximum facing velocity, measured adjacent to the nose of resting fish (about 4 inches off the bed), ranged from 6.5-7.8 ft/s and was unrelated to fish size (Table 6). Fish usually rested no more than 3 minutes between sprints. This suggests that, although adult shovelnose sturgeon can successfully move through these high velocities, they are not likely to maintain position for an extended period. On several occasions motivated fish were moved to the bottom and they immediately returned to the top.

Table 5. Comparison of movement success over four substrates at average velocities ranging from 0.8 to 6.0 ft/s in the adjustable slope flume.

Number reaching top/number tested

Velocity (ft/s)	0.8_d -1.1_n	1.2_d -2.0_n	1.6_d -2.5_n	2.0_d -3.3_n	2.2_n-6.0_u
Smooth	7/10	3/4	9/10	9/10	6/10
Coarse Sand	3/6	-	4/6	4/6	4/6
Gravel	4/6	2/6	5/6	-	2/6
Cobble	2/6	4/8	3/8	-	2/8
TOTAL	16/28	9/18	21/30	13/16	14/30
Percent	57	50	70	81	47

Table 6. Facing velocities of resting shovelnose sturgeon in the 30 foot flume and adjustable slope flume associated with test velocity. (Location of measurements varied along the flume.)

Velocity Test (ft/s)	Facing Velocity, (ft/s)	Fork Length (inches)
30 foot flume		
0.8 (smooth)	1.49	28
1.6 (sand)	1.48	31
2.0 (sand)	2.22	30
2.5 (sand)	2.75	30
2.5 (gravel)	3.05	31.5
3.5 (sand)	4.08	31
Adjustable slope flume		
2.2_n-6.0_u (smooth)	7.5	28
	7.8	31.5
	6.5	30.0
	7.6	33.5
coarse sand / gravel	6.6	35.0
cobble	>6.4	32.5

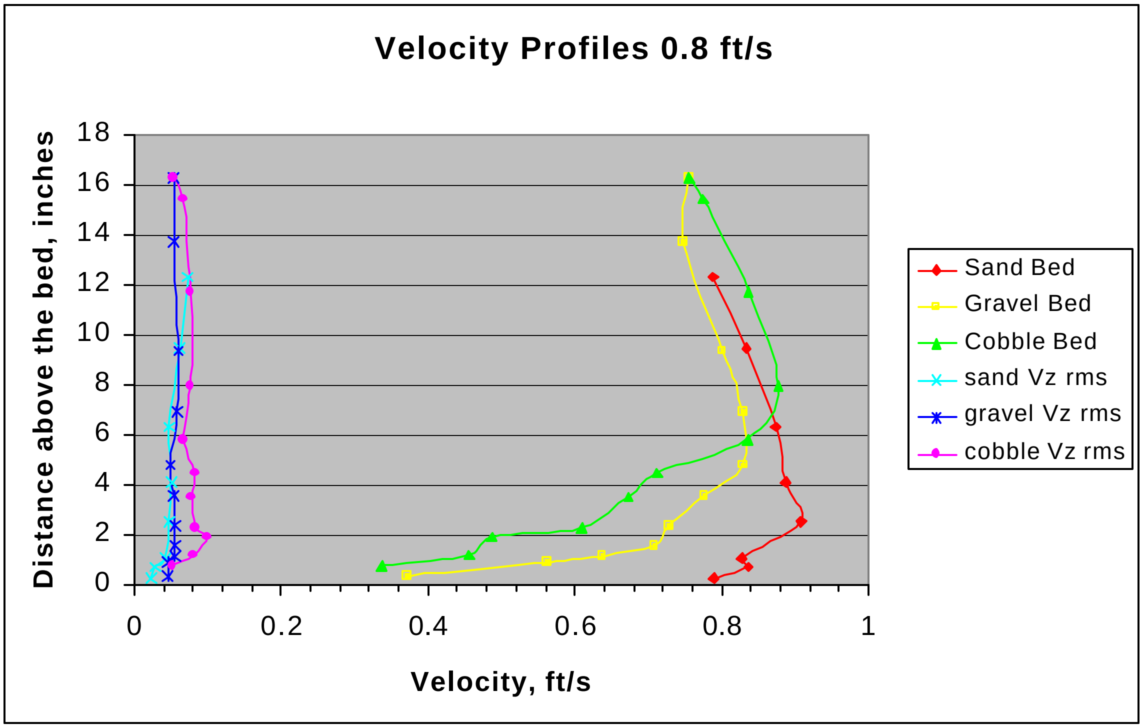


Figure 8 - Vertical velocity profiles measured over coarse sand, gravel and cobble beds for flume tests with an average flow velocity target of 0.8 ft/s.

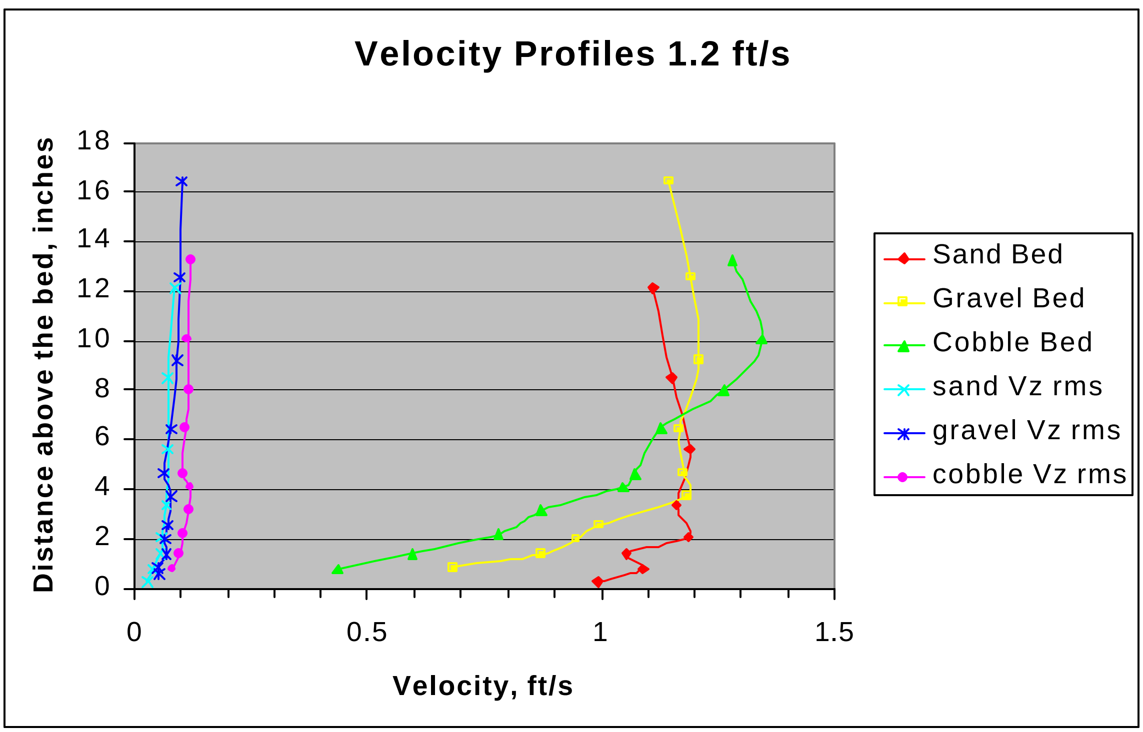


Figure 9 - Vertical velocity profiles measured over coarse sand, gravel and cobble beds for flume tests with an average flow velocity target of 1.2 ft/s.

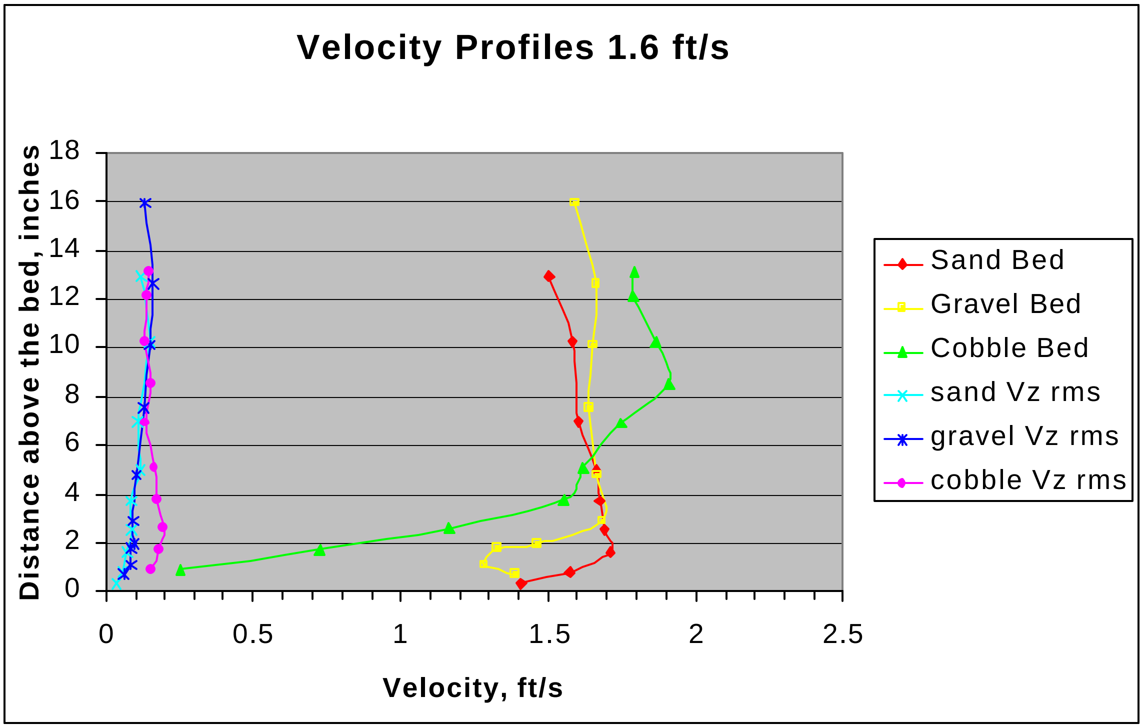


Figure 10 - Vertical velocity profiles measured over coarse sand, gravel and cobble beds for flume tests with an average flow velocity target of 1.6 ft/s.

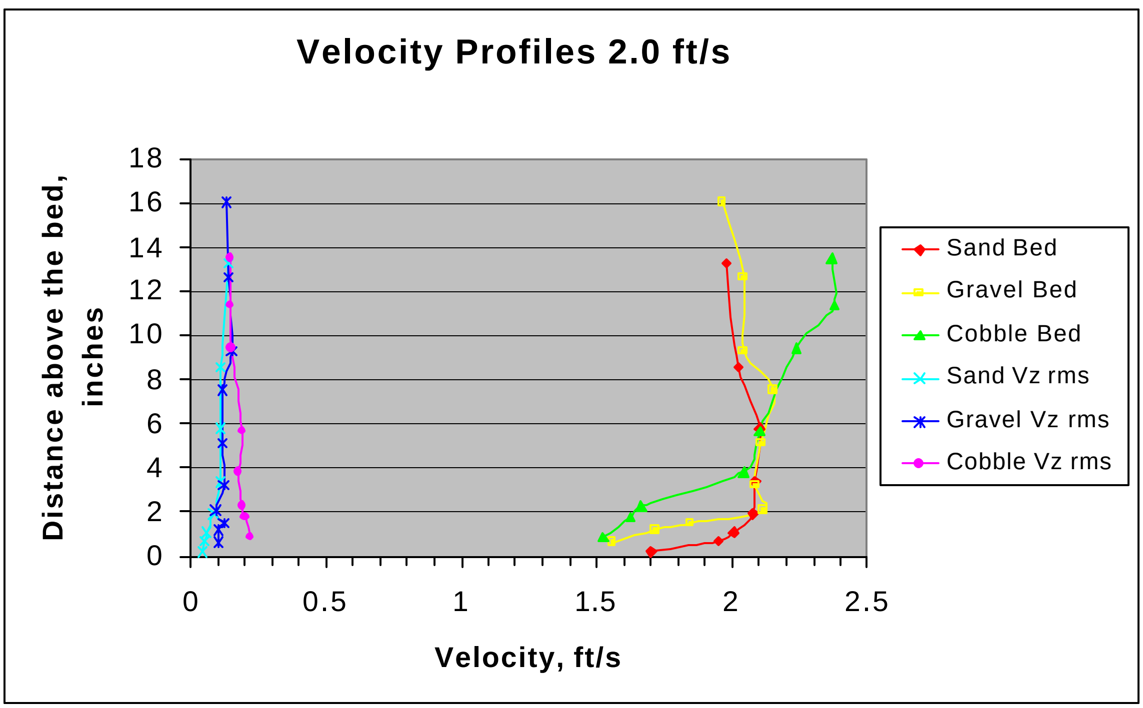


Figure 11 - Vertical velocity profiles measured over coarse sand, gravel and cobble beds for flume tests with an average flow velocity target of 2.0 ft/s.

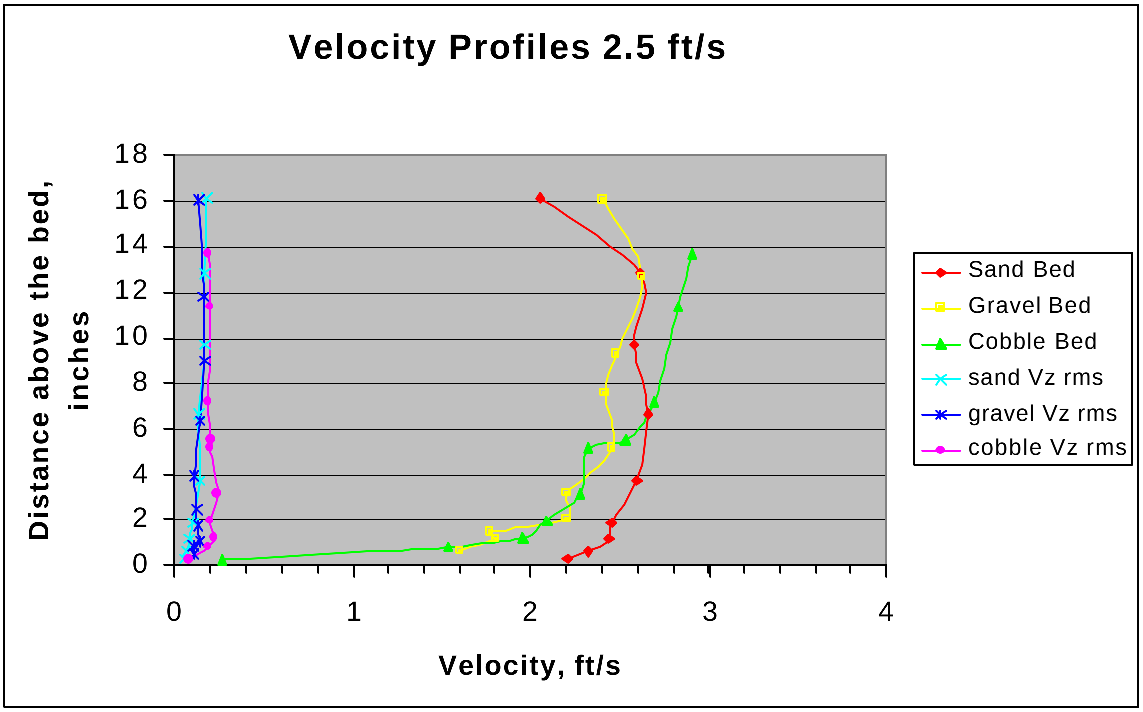


Figure 12 - Vertical velocity profiles measured over coarse sand, gravel and cobble beds for flume tests with an average flow velocity target of 2.5 ft/s.

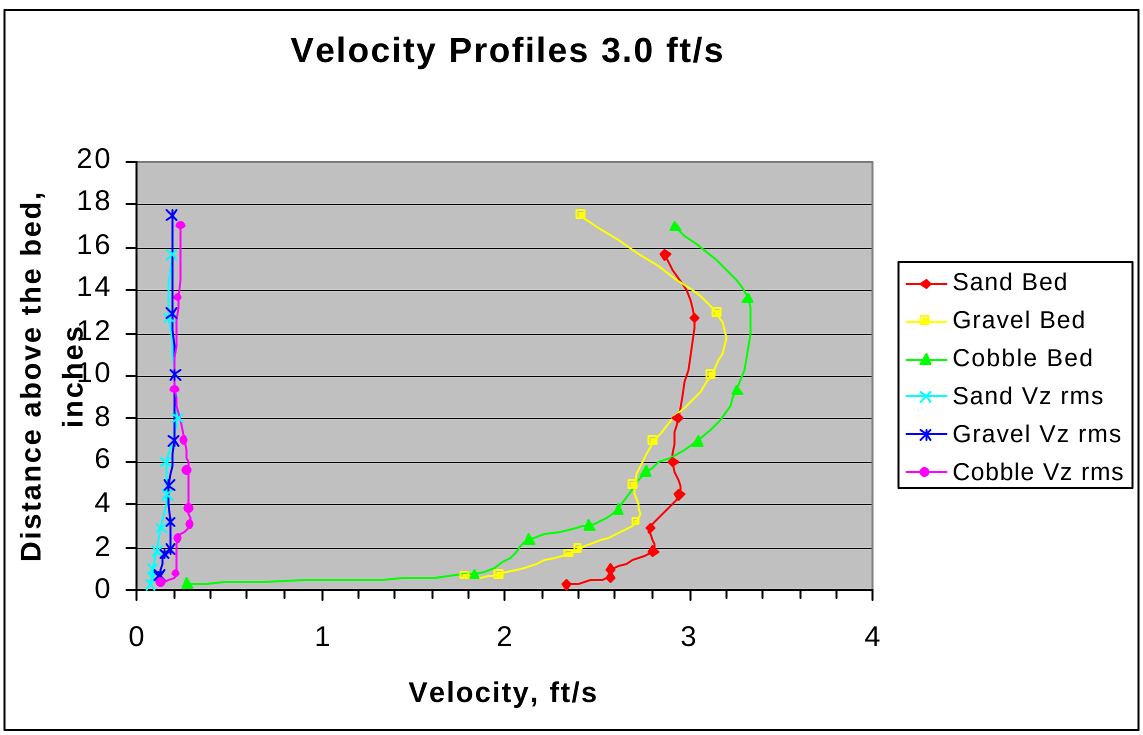


Figure 13 - Vertical velocity profiles measured over coarse sand, gravel and cobble beds for flume tests with an average flow velocity target of 3.0 ft/s.

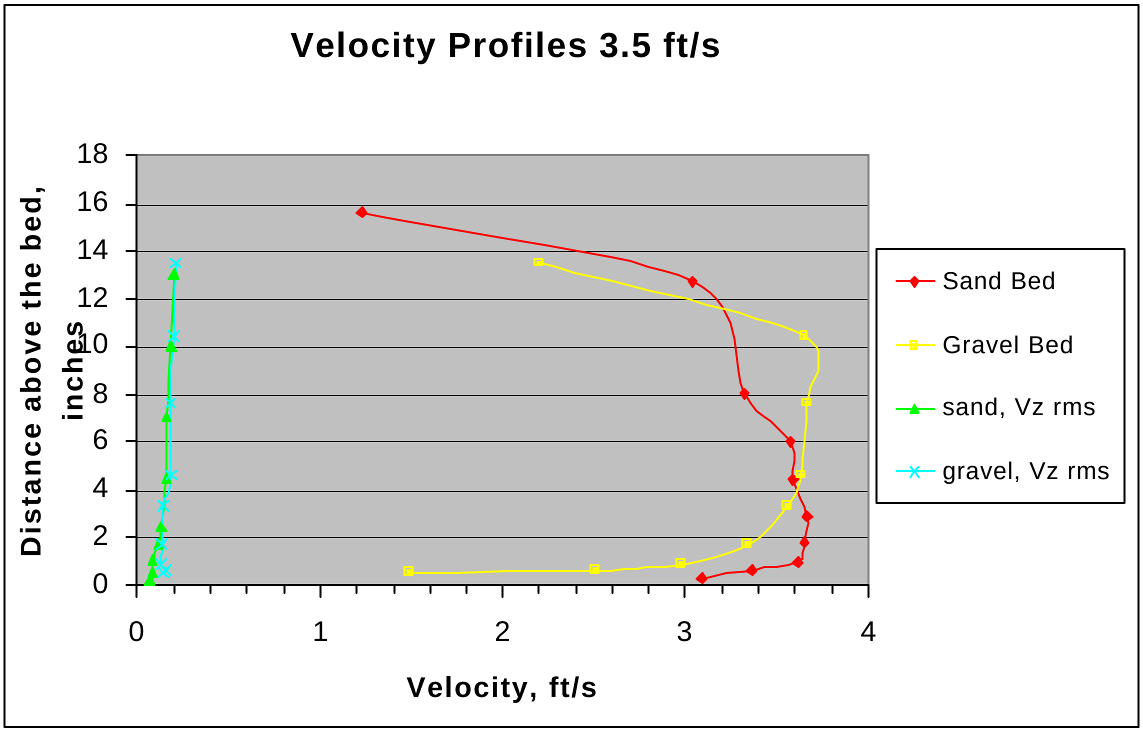


Figure 14 - Vertical velocity profiles measured over coarse sand and gravel beds for flume tests with an average flow velocity target of 3.5 ft/s.

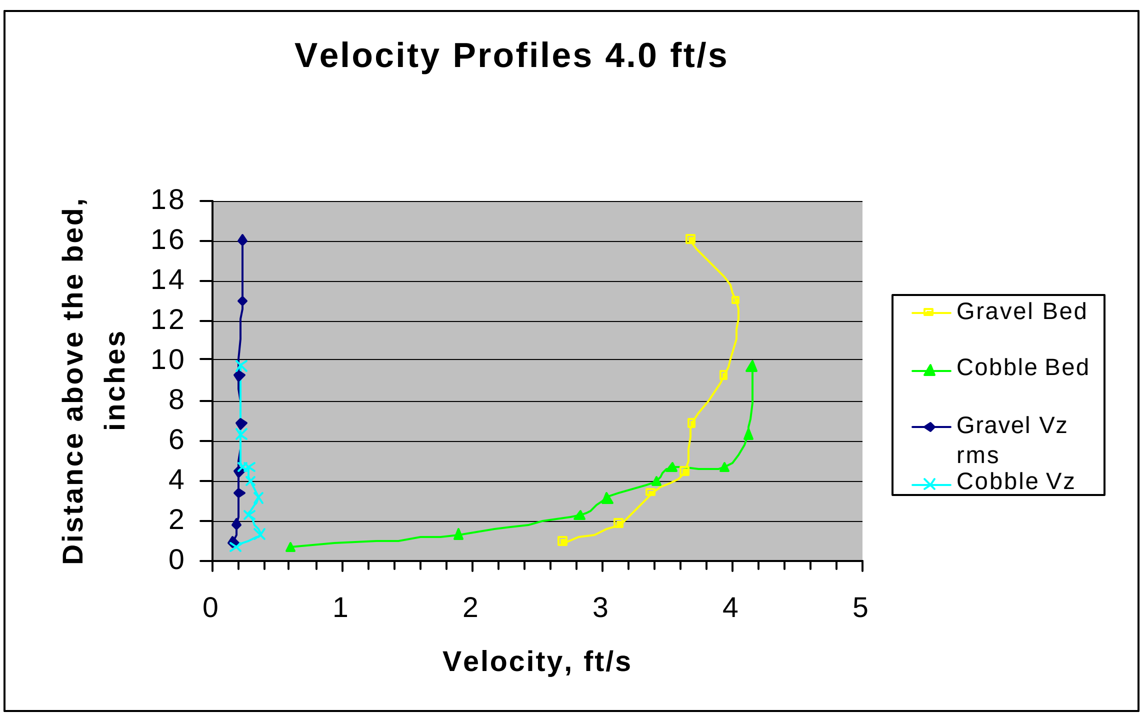


Figure 15 - Vertical velocity profiles measured over gravel and cobble beds for flume tests with an average flow velocity target of 4.0 ft/s.

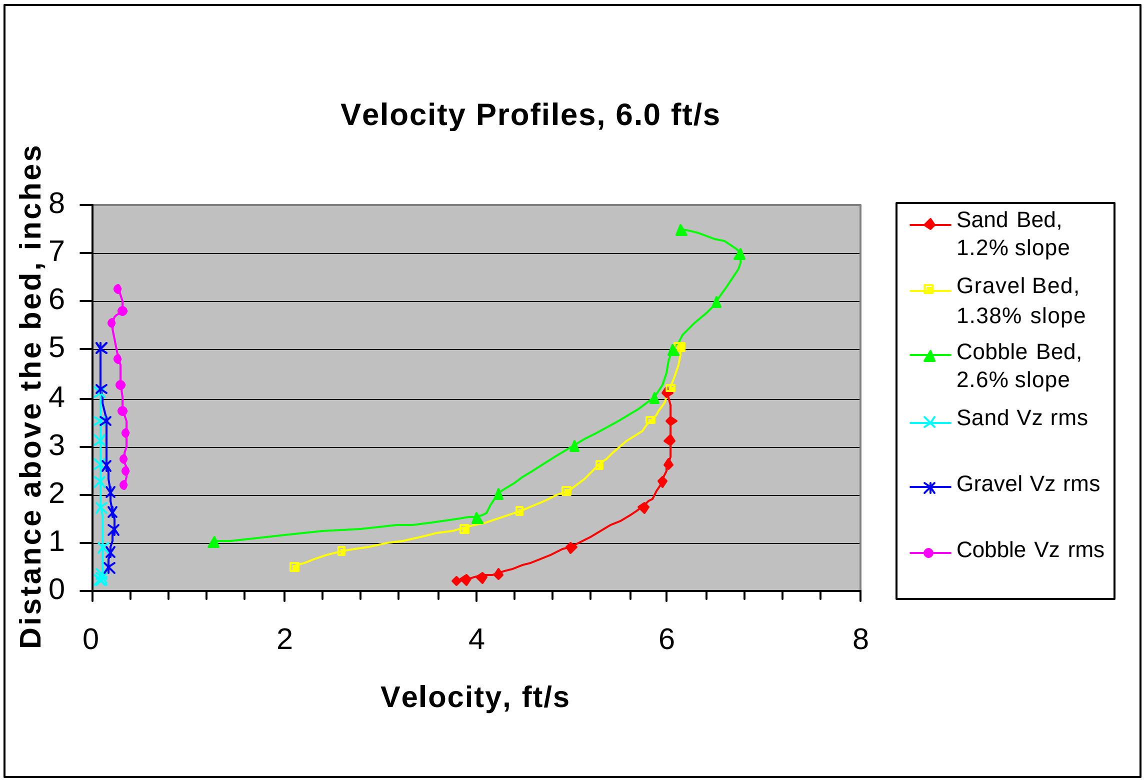


Figure 16 - Vertical velocity profiles measured over coarse sand, gravel and cobble beds for flume tests with a target average flow velocity of 6.0 ft/s.

Flow Turbulence

Vertical Baffles - Large Scale Horizontal Eddies

The importance of flow direction in the horizontal plane in relation to upstream fish movement was evaluated using vertical baffles of two different widths. Baffles were placed in the flume perpendicular to the back channel wall at a 6 ft spacing (Figure 17). Flow past each baffle was similar to that found in vertical slot fishways. Flow velocity accelerates through the slot then slows again in the downstream pool. Downstream and behind each vertical baffle, flow forms a large horizontally aligned eddy.

<u>Test Procedure</u> - Fish disorientation in relation to horizontal eddy scale was investigated using 4 tests of 2 vertical baffle widths. Baffle widths were chosen to represent about 50 percent and 75 percent of the average fish's body length. Tests were conducted for each baffle width using a range of average velocities (through slot velocity) of 0.8 ft/s to 4.0 ft/s. For these tests, flow depth was set at 18 inches and discharge

was adjusted to achieve the target slot velocity. Test procedures were identical to those in velocity/substrate tests except fish were moved to the downstream end of the flume at the beginning of each velocity trial.

Horizontal Eddy Test Results - Fish used in the tests resulted in baffle width to mean fish length ratios, (R_h) of 0.49 and 0.71 for the 15.5 inch and 22.5 inch wide baffles, respectively. Hydraulic conditions for each test are given in Table 7. Water surface differentials presented were measured using piezometer taps located near the flume floor between each baffle. The flow pattern encountered by fish downstream of each baffle is shown in Figure 18 for the maximum slot velocity tested. The velocity vector field was mapped for a distance of twice the baffle width downstream by measuring two dimensional point velocities on a horizontal grid. All velocities were measured at mid-depth. Flow through the vertical slot drives the circulation of the horizontal eddy. Behind the vertical baffles flow moves upstream along the back wall. For each baffle width, upstream flow extended out from the wall about two-thirds of the baffle width.

In tests of both baffle widths, at velocities below 2.5 ft/s there was considerable up and down movement within the pools between baffles, often circling in the area below the first baffle. In the tests of the 15.5 inch baffle (2 series of tests, R_h = 0.49) 66-75% of the fish moved to the top at velocities of 2.5 ft/s and above. At these velocities, fish that had moved to the top in the previous trial resisted being moved down-channel between trials and fish that moved up did so immediately when flow was increased. Fish that passed the first slot usually continued to the top without holding. Tests of the 22.5 inch wide baffle (2 series of tests, R_h = 0.71), showed that fish navigated the channel successfully at low velocity (1.6 ft/s) but displayed considerable upstream disorientation at 3 ft/s and higher velocities (see Table 3). Fish often moved upstream between baffles in the upstream eddy current. The current would propel the fish suddenly upstream resulting in the fish striking the upstream baffle or turning and swimming vertical along the downstream baffle face then circling downstream.

Table 7. Test variable - Ratio of baffle width to mean fish length, (R_h).

Slot Flow Velocity Target, ft/s (Average)	Measured Flow, ft^3/s		Measured Water Surface Differential between Baffles, ft	
	15.25 inch Wide Vertical Baffle, R_h = 0.49	22.5 inch Wide Vertical Baffle, R_h = 0.71	15.25 Inch Wide Vertical Baffle, R_h = 0.49	22.5 inch Wide Vertical Baffle, R_h = 0.71
0.8	2.08	1.94	0.01	0.015
1.6	4.15	2.97	0.04	0.04
2.0	6.48	3.7	0.06	0.07
3.0	9.08	4.9	0.14	0.12
3.5	11.67	5.8	0.21	0.18
4.0	NA	6.6	NA	0.27

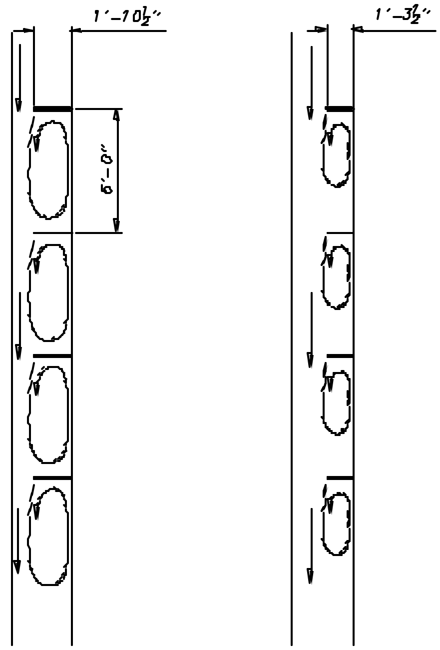


Figure 17 - Plan view of flow past vertical baffles in test flume.

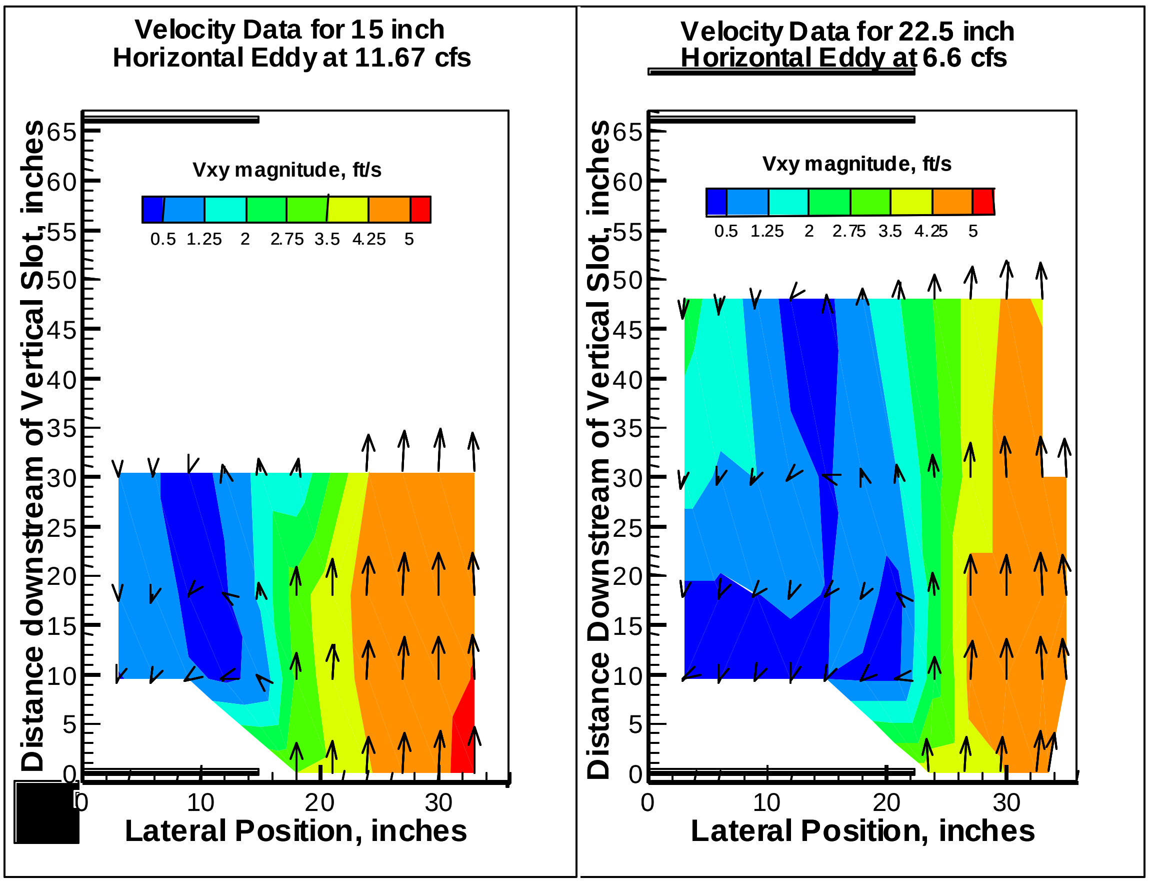


Figure 18 - Plan view of the velocity vector field measured downstream of vertical baffles.

Weir Baffles - Large Scale Vertical Eddies

The importance of flow direction in the vertical plane in relation to upstream fish movement was evaluated using baffles installed as weirs at four different heights. Baffles were mounted on the floor of the flume at a 6 ft spacing (Figure 19). Flow past each baffle was similar to that found in pool and weir fishways. Flow velocity accelerates across the weir then slows again in the downstream pool. Downstream and behind each baffle, flow forms a large vertical eddy. Flow circulates within the eddy with flow above the baffle (weir crest) moving downstream and flow behind the baffle moving upstream (Figure 20).

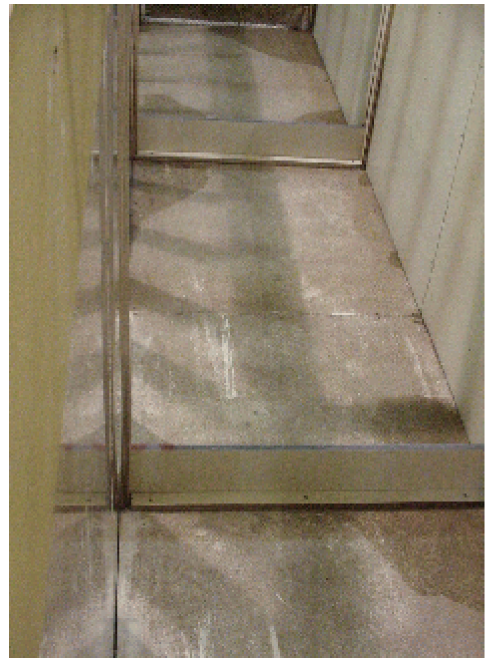


Figure 19 - View of 6 inch high weirs used to induce large scale vertical oriented eddies in the flow along the invert of the test flume.

Test Procedure - To evaluate the influence of large scale vertical turbulence, we examined sturgeon behavior related to 3, 6, 12, and 21 inch cross channel baffles, at eight velocities over sand substrate. The flow depth over each baffle was held constant at 18 inches. Fish used in the tests resulted in baffle height to mean fish length ratios, (R_v) of 0.09, 0.19, 0.38 and 0.67 for the 3 inch, 6 inch, 12 inch and 21 inch high baffles, respectively. Two fish were used in each of seven tests (52 trials); each velocity trial was 20 minutes duration. Sturgeon that successfully negotiated the flume (made it to the top) were moved to the bottom before the next velocity increase.

Vertical Eddy Test Results - Water surface differentials measured upstream to downstream across the baffles are given in Table 8. The flow pattern encountered by fish downstream of 3 inch, 6 inch and 12 inch baffles is shown in Figures 21 to 23 for weir velocities of 1.6 and 3.0 ft/s. The velocity vector field was mapped over a vertical plane downstream of a baffle. All velocities were measured at mid-channel. Behind the baffles flow moves upstream from the channel floor to about the height of the baffle crest.

Table 8. Test variable - Ratio of baffle height to mean fish length ratio,(R_v)

Flow Velocity Target over the Weir, ft/s (Average)	Depth Above Weir, ft	Measured Flow, ft^3/s	Measured Water Surface Differential Across Weir, ft			
			3 inch High Weir, $R_v = 0.09$	6 inch High Weir, $R_v = 0.19$	12 inch High Weir, $R_v = 0.38$	21 inch High Weir, $R_v = 0.67$
0.8	1.5	3.6	0.01	0.015	0.015	0.01
1.2	1.5	5.0	0.015	0.02	0.02	0.015
1.6	1.5	6.9	0.02	0.03	0.03	0.025
2.0	1.5	8.5	0.03	0.035	0.03	0.04
2.5	1.5	11.0	0.045	0.05	0.07	0.07
3.0	1.5	13.5	0.06	0.10	0.10	0.14
3.5	1.5	16.0	0.08	0.13	0.13	0.17
4.0	1.5	17.5	0.10	0.25	NA	NA

Fish negotiated all baffles tested, but percent success declined with baffle height (see Table 3, Weir Baffle Tests). The two fish in the 21 inch baffle test did not pass the first baffle 78% of the time; each reached the top only once (at 1.2 ft/s and 3 ft/s). Overall passage success (all baffle tests) increased with increasing velocity up to 2 ft/s, then leveled off at about 70%; if the results from the 21 inch baffle are excluded, success levels off at about 83%. For 3, 6 and 12 inches baffles, success was 75-100% at all velocities tested between 2.0 and 4 ft/s. The lowest overall success rate was 14% at 0.8 ft/s. At this velocity, 8 of 14 fish tested did not pass the first baffle. Milling behavior was common at 0.8 ft/s and 1.6 ft/s and nearly all down-channel movement was head first suggesting poor flow orientation. At 2.0 ft/s and above, most down-channel movement was tail first suggesting much stronger flow orientation. Another indication of flow attraction is how quickly fish moved to the top. Excluding the 21 inch baffle data, at velocities of 1.6, 2.0, 2.5, 3.0, 3.5, and 4 ft/s, 3 of 12 (25%), 6 of 12 (50%), 8 of 12 (67%), 8 of 11 (73%), 6 of 6 (100%), 6 of 6 (100%), respectively, moved up immediately when velocity was increased. Once a fish immediately moved to the top, it almost always moved up immediately in subsequent velocities tested. No fish in the 21 inch baffle tests moved up immediately, as well as two fish in the 12 inch baffle test. These two fish were impinged and removed during the 3.0 ft/s test.

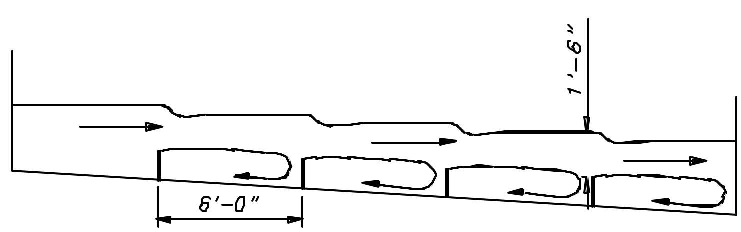


Figure 20 - Elevation view of flow over weir baffles in the test flume.

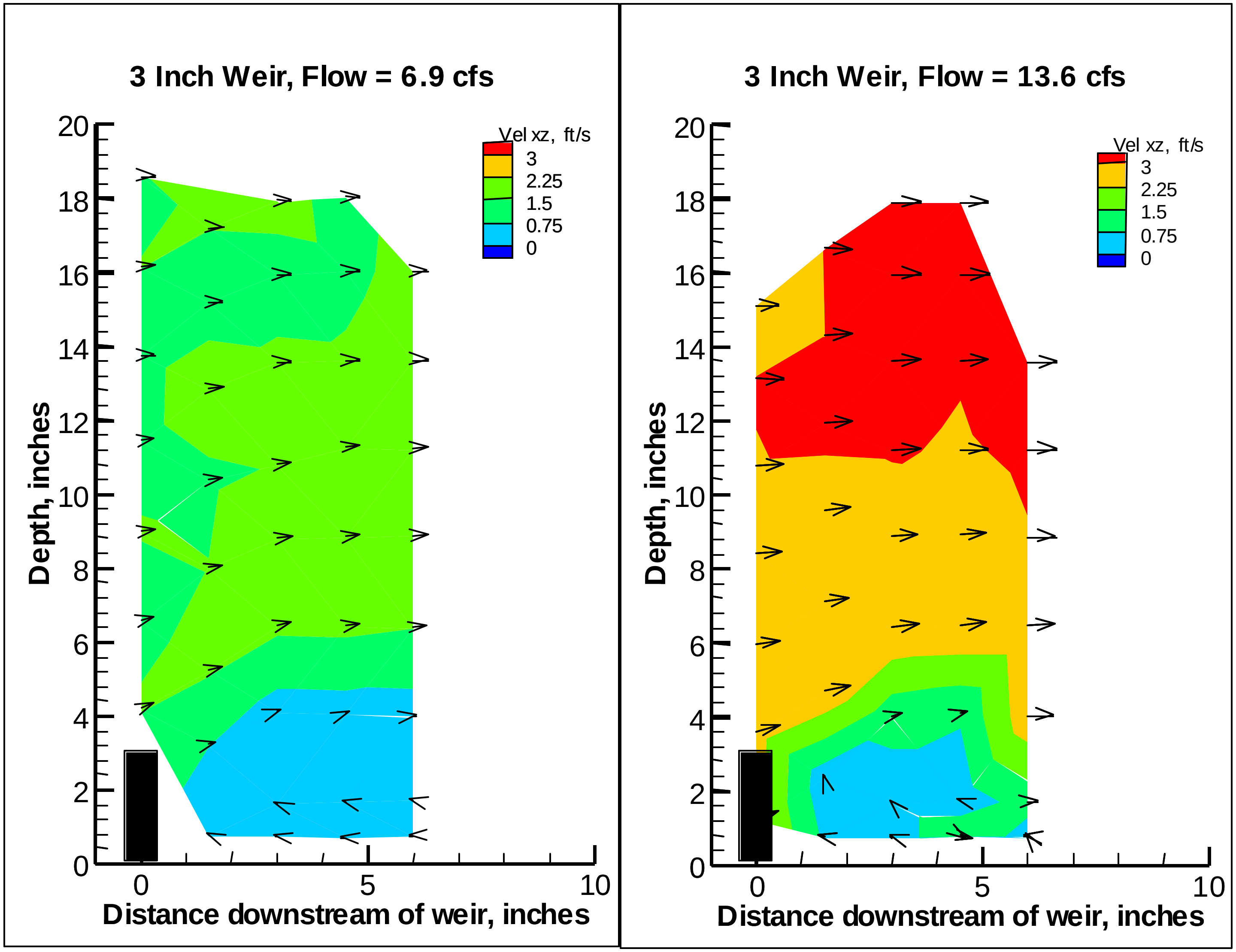


Figure 21 - Elevation view of measured velocity vector field downstream of 3 inch high weir baffles.

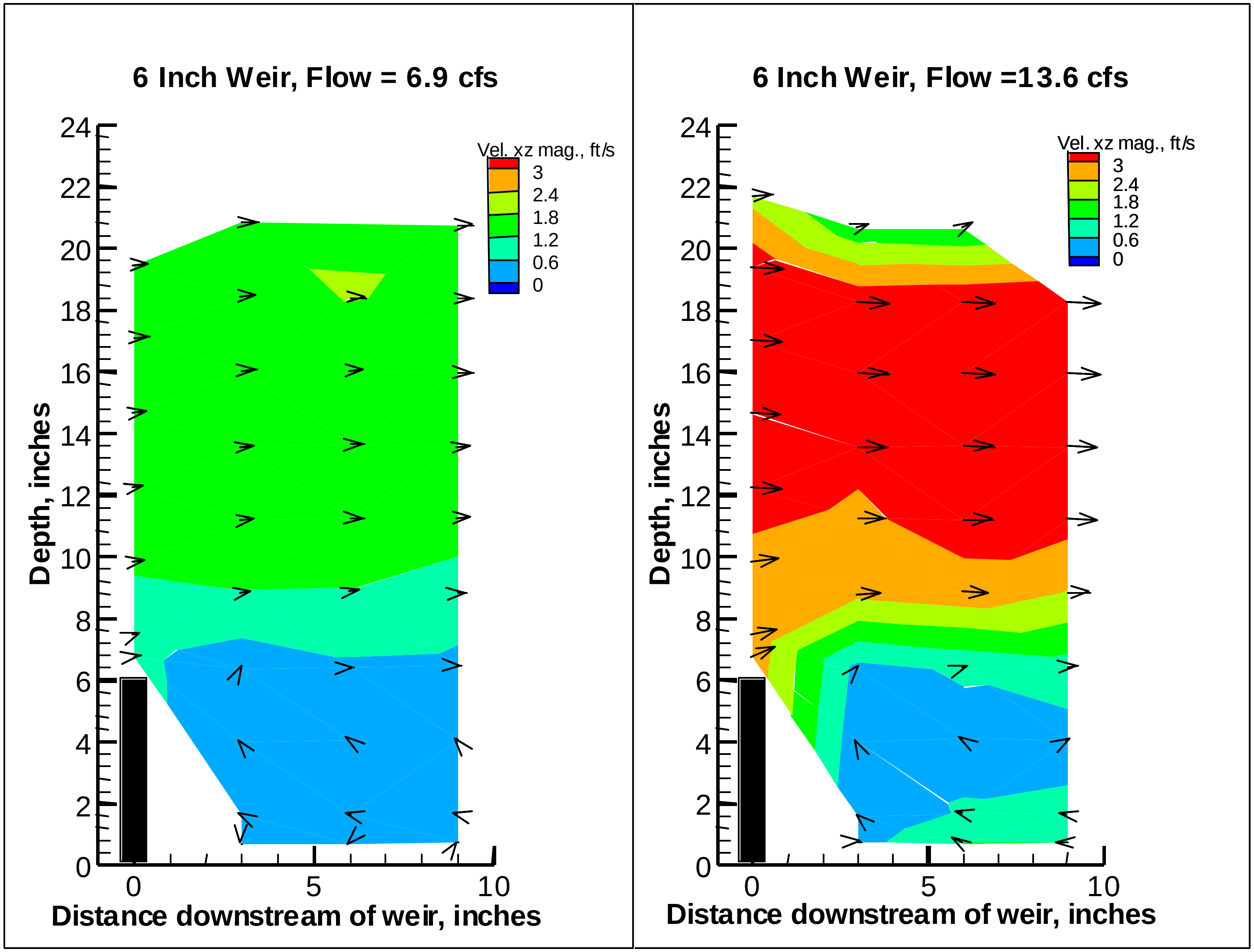


Figure 22 - Elevation view of measured velocity vector field downstream of 6 inch high weir baffles.

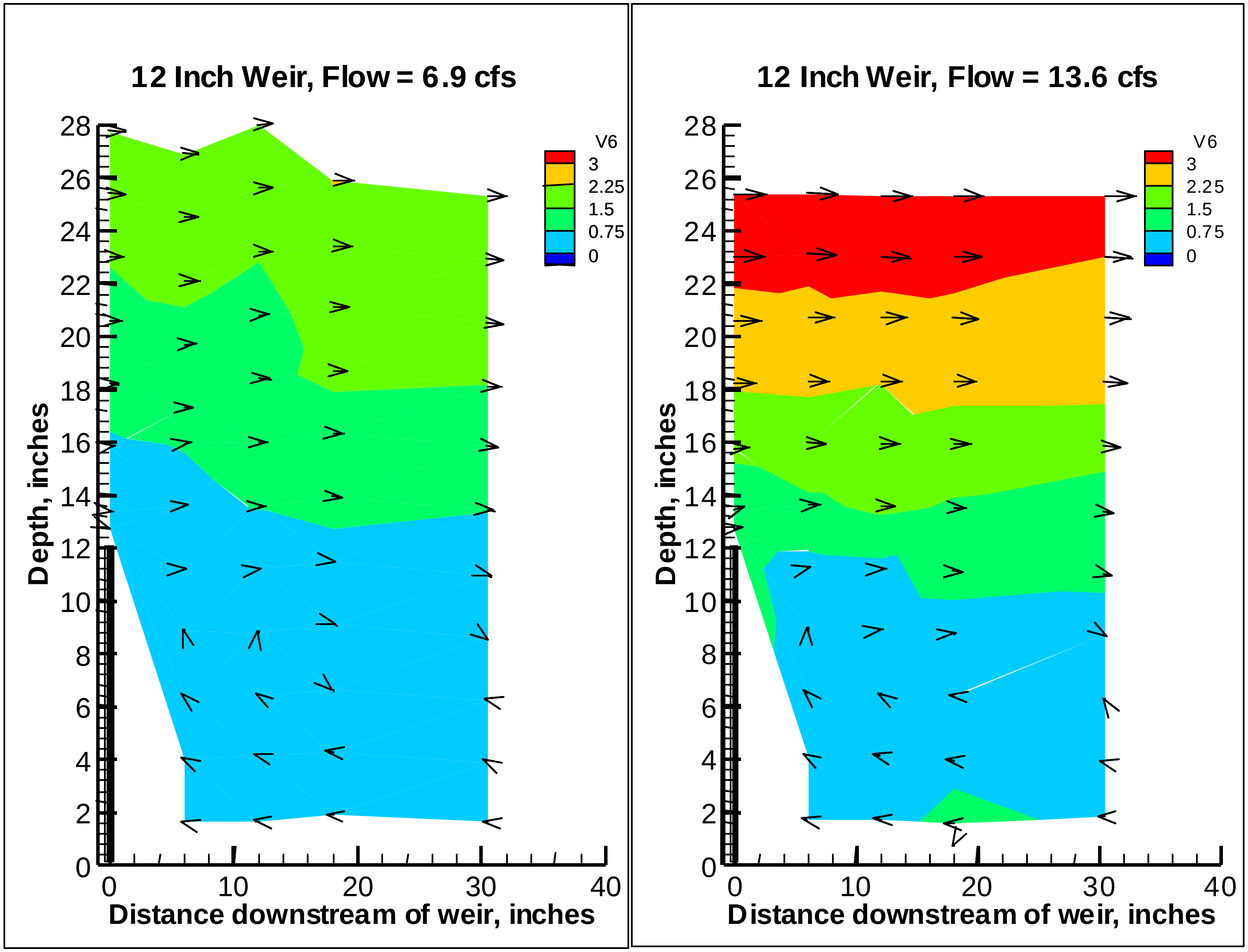


Figure 23 - Elevation view of measured velocity vector field downstream of 12 inch high weir baffles.

Fishway Studies

The U.S. Bureau of Reclamation, Water Resources Research Laboratory, maintains three prototype scale test fishways for evaluating passage of non-salmonids native to the western United States. During the sturgeon study these fishways were used to observe sturgeon passage and behavior in response to fishway flow conditions of different fishway geometries. All fishway tests were conducted at similar flow depths and passage velocities.

Test Apparatus

Two of the fishways are used for testing different baffle designs for flume type fishways. For the sturgeon studies, two different forms of vertical slot fishway baffles were tested in the flumes. The flumes are 5.5 ft wide by 5.5 ft deep by 30 ft long with a 5 % bottom slope. A standard vertical slot baffle design (FWS, 1997) was placed in one fishway and a Reclamation designed chevron shaded duel-vertical-slot baffle was tested in the second. Vertical slot baffle is a generic term that refers to a flow baffle that has full depth openings (slots) that allow fish passage at any depth. Different vertical slot baffle designs create different flow patterns within the pools between baffles. The vertical slot baffle designs tested are shown in Figures 24 and 25. In the laboratory tests, all baffles were spaced 6 ft apart.

The third fishway is a 70 ft long section of a rock lined bypass channel with boulder weirs (Figure 26). The fishway is designed to test fish passage through a rock fishway with different configurations of rock baffles. The fishway is a trapezoidal channel at a 2.0% slope with a 4 ft wide bottom, 2:1 side slopes 4 ft deep. The channel is constructed of riprap with a gradation of 15 percent (D_{15}) smaller than 5 inches and 85 percent (D_{85}) smaller than 15 inches. Two foot to 3.5 ft diameter boulders are placed in the flow to form control sections. Boulders are placed with a 2 ft wide space between boulders in a upstream pointing chevron pattern. The boulder pattern is designed to create a flow pattern of highest velocity in the center of the channel and lowest velocities along the banks, giving fish a choice of flow conditions. In the model, artificial boulders are use to facilitate placement. The model boulders are constructed of concrete mortar placed over wire lath.

Test Procedure

All fishway tests were conducted with the second group of fish which were collected from the Yellowstone River on October 16, 2001. In general, these fish were less motivated to move than the group of fish collected in July. Fish were handled as in other tests. Fish were released at the bottom of the fishway and movement behavior recorded. Fish behavior at two velocities (2.5 - 4.0 ft/s) and associated differentials across slots (0.12- 0.35 ft) was evaluated in each test. Velocity was altered by manipulating tail boards.

View of standard vertical slot baffle fishway looking downstream.

View of chevron shaped duel-vertical slot baffle fishway looking downstream.

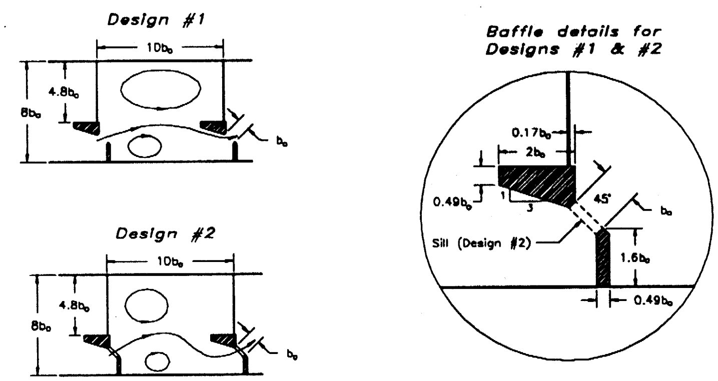


Figure 24 - Standard vertical slot fishway baffle design, FWS, 1997.

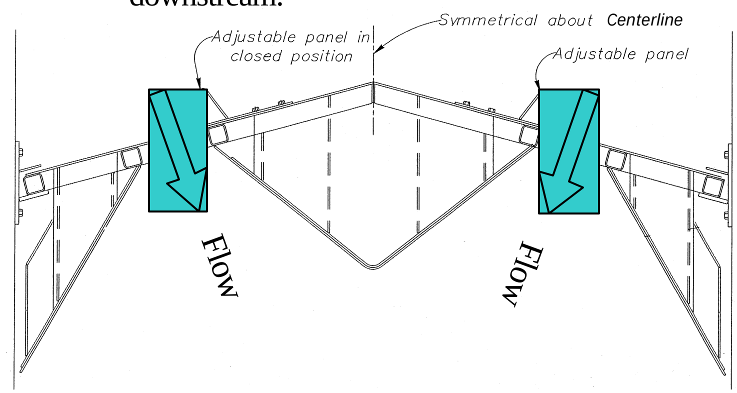


Figure 25 - Reclamation chevron shaped duel-vertical slot baffle design.

Fishway Test Results

Standard Vertical Slot Fishway - Only two of eight fish tested (four tests) in the standard vertical slot fishway were successful in passing all four slots (Table 9). One passed when slot velocity was 2.99 ft/s with a differential water surface between pools of 0.26 ft and the other when slot velocity was 3.8 ft/s with a differential of 0.31ft. In general, as velocity was increased, fish activity increased. At the lowest velocities tested, all fish typically circled both counterclockwise and clockwise. At higher velocities, most movement was counterclockwise. When stationary, fish were typically located at the bottom net on the slot side with the tail in the corner and the body at a 45 degree angle or holding parallel to the slot wall with the tail near the slot opening. One fish passed all four slots in 4 minutes once passage was initiated. This fish stayed mostly on the slot side and out of the eddy. The second successful fish took 30 minutes to pass all four slots once passage began. Passage began soon after slot velocity was increased to 3.8 ft/s (differential 0.31 ft). The fish passed the first two slots in succession, then circled in the eddy and held with the body about 3/4 through slot 2. Then moved up and held parallel to slot 3 wall facing away from the slot. Movement through slots 3 and 4 was not observed but occurred in less than 5 minutes.

Table 9. Evaluation of passage success of eight shovelnose sturgeon in the standard vertical slot fishway.

Date	Flow (ft^3/s)	Velocity (ft/s) (Measured point velocity in slot)	Average Differential, (ft)	Fork length, (in)	Passage Time, Minutes (after passing first baffle)
10/29/01	3.43	---	0.20	31.5	---
				35.5	---
		2.99	0.26	31.5	4
				35.5	---
		3.9	0.33	31.5	---
				35.5	---
	3.31	2.6	0.15	31.0	---
				28.5	---
		3.3	0.24	31.0	---
				28.5	---
		3.8	0.31	31.0	30
				28.5	---
	3.32	2.5	0.12	30.0	---
				33.5	---
		3.7	0.24	30.0	---
				33.5	---
11/05/01	3.37	---	0.14	31.5	---
				33.0	---
		---	0.26	31.5	---
				33.0	---
		---	0.31	31.5	---
				33.0	---

Duel Slot Fishway - The duel vertical slot fishway baffle was developed to minimize large scale eddies within a fishway and maximize the cross sectional area of downstream flow. The objective was to improve streamwise fish orientation within the fishway. Flow through the duel slot baffle forms slender eddies (horizontal) along the flume walls bracketing a wide center area of downstream flow. We conducted five tests of the duel slot fishway. Although fish were more motivated to move in this fishway compared to the standard slot fishway, only 2 of the 10 sturgeon tested successfully negotiated the 4 sets of duel slots. One reached the top in 16 minutes and the other in 53 minutes (Table 10). Four others moved past the first duel slot (two up to slot 2, one up to slot 3 and one to slot 4). Fish tended to be bounced around quite a lot below the first set of slots. When fish were stationary, they generally held in the middle of the channel between the slots, facing into the flow. Four of the 10 fish either did not move or moved very little. Others showed considerable up and down channel movement and circling clockwise between sets of slots. Down channel movement was mostly tail first, but not always.

Table 10. Evaluation of passage success of 10 shovelnose sturgeon in the duel slot fishway.

Date	Flow (ft^3/s)	Velocity (ft/s)	Differential (ft)	Fork Length (inches)	Minutes (after passing first baffle)
10/30/01	5.75			29.5	---
				33.0	---
	5.75			30.5	---active below 3
				31.5	---active below 4
	5.75			31.5	---
				35.5	53
11/02/01	6.25	2.8	0.13	31.5	---
		2.8	0.14	30.0	---
11/05/02	6.0	2.8	0.13	30.5	16
		2.9	0.14	28.5	Active below 2
		3.5	.18		

Rock Fishway - We conducted 12 tests of the rock fishway. Hydraulic conditions within the fishway were similar for all tests. Fishway flow depth was varied during some tests to improve observation of fish from the surface. Of the three fishways tested, passage success was much superior in this fishway. Fifteen of the 24 fish tested (62.5%) successfully negotiated the fishway (Table 11). Passage time ranged from 14 to 83 minutes (mean 38.9 minutes). Motivated fish had no difficulty negotiating the rock fishway. Movement was usually up channel and movement pattern was very consistent. Fish typically moved up the left side of the channel into the turbulence, then moved across the channel and held briefly. This position was very consistent, with nearly all fish holding in the same area. The fish would then move up into the turbulence in the middle of the channel, then gradually move over below boulders 1 and 2 (right) and pass through the gap between these boulders, holding just above them, often with the tail just above or in the gap. The velocity in the gap was 4 ft/s. The pattern of passage through each boulder group was very predictable and consistent. Fish appeared to search for the best hydraulic conditions available for passage. Only two fish that passed the first boulder group did not pass the other two. Seven fish were not motivated to move and remained near the bottom net throughout the tests.

Figure 26 - View looking downstream at rock lined fishway channel with boulder weirs.

Table 11. Evaluation of passage success of 24 shovelnose sturgeon in the rock fishway.

Date	Flow (ft^3/s)	Velocity (ft/s) (flow velocity between boulders)	Differential (pool to pool) ft	Fork length inches	Minutes
10/29/01	16.0	---	---	31.5	70
				29.5	---
	16.0	---	---	31.0	18
				30.5	25
	16.0	---	---	28.5	14
				30.5	---
11/01/01	14.6	3.3 - 4.4	2.2	32.5	83
				30.0	50
	14.6	3.3 - 4.4	2.3	30.0	---
				28.5	---
	13.0	---	---	29.5	33
				34.5	69
	14.0	---	---	30.0	---
				31.5	---
11/02/01	14.1	3.7 - 4.2	.19	31.5	15
				28.5	23
	14.1	3.5 - 4	.17	31.5	45
				30.0	48
	14.1	3.7 - 4.2	.19	31.0	31
				28.5	---
	14.1	3.5 - 4.1	.19	30.0	---
				32.5	---
	14.0	---		35.5	30
				31.0	30

Summary/Discussion

Fifty three tests and 204 trials (Table 12) to evaluate the behavioral response of adult shovelnose sturgeon to velocity, substrate, horizontal turbulence, vertical turbulence, and three prototype fishways were conducted during the study for a total of approximately 71 hours of observations. Test fish were obtained from the Yellowstone River, Montana in July and October 2001. Fork length ranged from 25.2 to 35.5 inches and weight ranged from 3.1 to 10.6 pounds. Tests were conducted July 24-31 (30 ft flume), August 1-3 (Adjustable slope, sand and gravel bed), August 27-31 (horizontal and vertical baffles), September 25-29 (adjustable slope, cobble bed); and Oct. 29 -Nov. 7 in the three fishway models.

Test fish were very docile and showed no apparent response to observers, simplifying experimental concerns. The only observable stress experienced by test fish occurred when a fish either got tangled in the up- or down-channel netting by its scutes or when it collided with a baffle. In both cases, fish would return to or stay at the bottom of the channel and remain there for the remainder of the test. Forceful collisions with baffles were not uncommon and these, as well as apparent lack of response to light suggest that eye sight is of little important in sturgeon navigation. Preliminary tests holding velocity constant and varying depth revealed that velocity, rather than depth was important in attraction and orientation so depth was eliminated as a test variable.

Sturgeon successfully negotiated the range of average velocities tested (0.8-6.0) over all substrates (smooth, fine sand, coarse sand, gravel and cobble) evaluated. As substrate grain size increased, movement success declined, but relatively small sample size and large variability precluded definitive conclusions. However, general trends were similar in both the 30 foot flume and the adjustable slope flume, with poorest movement success over cobble.

Pattern of successful movement related to velocity was consistent among substrates and among all test conditions. Flow orientation and attraction became strong at about 2 ft/s and remained strong at higher velocities tested. At velocities of 0.8 and 1.6 ft/s, fish showed poor orientation to flow as indicated by milling behavior, downstream head first movements and longest average time to reach the top of the channel. At velocities of 2 - 6 ft/s, strong flow orientation was apparent and down-channel movement was nearly always tail first. Average percent success in negotiating the channel at the highest velocities tested dropped from 81-87% at 4 ft/s, to 47% at 6 ft/s. Although adult shovelnose sturgeon could successfully move through and hold in high velocities, they did not hold long and would not be expected to maintain position at these velocities for extended periods.

Although sturgeon were able to negotiate horizontal and vertical eddies tested, larger eddies tended to cause delays. Generally, as eddy size increased, success in passage decreased. This pattern was also seen in the standard vertical slot and the duel slot prototype fishways. Velocity orientation in horizontal and vertical eddy tests was similar to other tests. At velocities below 2 or 2.5 ft/s, orientation was poor and fish tended to be less flow oriented. At higher velocities, undirected movement declined.

All prototype fishway tests were conducted using shovelnose sturgeon collected in October 2001. These fish appeared to be less motivated to move. However, fishway tests were instructive. Some shovelnose sturgeon successfully maneuvered all three fishways tested. In both the vertical slot and duel slot fishways, fish appeared disoriented and passage success was poor. In the rock fishway, passage success was much improved, with 62.5% of the 24 fish tested reaching the top. In an effort to determine if poor success in the other fishways was due to using fish not motivated to move, we tested two fish in both fishways that had successfully negotiated the rock fishway. Only one of these four fish negotiated the fishway (duel slot).

Fishway Design Recommendations

Fishway Attraction Flow

Fishway attraction velocity should be between 2 to 4 ft/s. Ideally, these velocities should be sustained to the thalweg of the river. In the study, flow depth was not found to alter shovelnose sturgeon behavior in the range tested (0.7 ft to 4.5 ft). However, there are many attraction and predator avoidance benefits to having flow depths of about 4 ft or more when flow does not limit fishway operation. The studies of large scale eddies show attraction flow should provide a uniform transition between the fishway and the downstream river flow. Large eddies created by structures in the flow or poor alignment of merging flows may mask the fishway attraction flow.

Fishway Passage Velocity

The shovelnose sturgeon showed strong upstream movement at flow velocities of between 3.0 to 4.0 ft/s. In this velocity range, many test fish were able to actively swim for periods of 10 minutes or more. We recommend maximum fish passage velocities for design conditions be in the range of 3.0 to 4.0 ft/s.

Fishway Type

Based on our tests, we recommend a natural channel or rock channel fishway design for passage of sturgeon at Intake Diversion. In addition to positive results with sturgeon, this fishway provides a diversity of velocities and would better accommodate other fish species using the pass. Due to the significant river ice that forms near the dam, alternative construction techniques to riprap should be considered such as fabricated cable tied mats. These types of lining materials may provide cost effective low maintenance alternatives to a riprap lined fishway structure.

Table 12. Summary of tests conditions evaluated, number of sturgeon tested, number of tests conducted, and number of trials completed. (Each test used 2 fish and consisted of up to eight trials (velocities)).

Experimental condition	# Fish	# Tests	# Trials
30 foot flume			
Sand	4	2	14
Gravel	4	2	16
Cobble	4	2	16
Adjustable slope flume			
Smooth	10	5	22
Coarse gravel	6	3	12
Gravel	6	3	12
Cobble	8	4	15
Vertical baffles			
15.5 inch	4	2	11
22.5 inch	4	2	6
Horizontal baffles			
3 inch	4	2	14
6 inch	4	2	16
12 inch	4	2	14
21 inch	2	1	8
Vertical slot fishway	8	4	11
Duel slot fishway	10	5	5
Rock fishway	24	12	12
TOTAL	106	53	204

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