CRITERIA FOR A VELOCITY-BARRIER DAM FOR MIGRATING ADULT SALMONIDS

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ABSTRACT

Experiments were conducted in 1969 at the Fisheries Engineering Research Laboratory at Bonneville Dam on the Columbia River to develop standards for a velocity-barrier dam as a block to adult fish passage. Fish used in the experiment were chinook salmon (Oncorhynchus tshawytscha), coho salmon (O. kisutch), and steelhead (O. mykiss, formerly Salmo gairdneri); all salmon were fall-run migrating adults. During the tests, salmonids were completely blocked by a velocity-barrier dam with a 4.6-m long apron under the following conditions: 1) a vertical dam height of 0.91 m with a 0.3 m head of water and 2) a vertical dam height of 1.22 m with a 0.61 m head of water. When a bypass Denil fishway was operated in conjunction with the barrier dam, a vertical dam height of 0.61 m with a 0.3 m head of water blocked 100% of the chinook salmon, 98% of the coho salmon, and 93% of the steelhead.

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BACKGROUND

Fish barrier dams were developed on the Pacific coast of the United States to block upstream passage and collect anadromous fish [primarily Pacific salmon (Oncorhynchus spp.) and steelhead (O. mykiss formerly Salmo gairdneri)]. The dams were needed because the fish-rack barriers, which were commonly used at the time, were difficult to maintain and tended to accumulate debris (described by Clay 1961).

Two basic designs of fish barrier dams were developed. The simplest, a drop-barrier dam, incorporates a drop sufficient to stop fish at all stream flows. The other, a velocity-barrier dam, incorporates a shallow high-velocity flow on a flat apron at the base of a relatively low dam.

Drop-barrier dams were designed in the mid-1950s under the Department of Interior's Columbia River Development Program to prevent fish from ascending waterfalls or migrating upstream beyond a hatchery. With salmon and steelhead, 3.05 m[1] was established as a minimum drop, but 2.44 m was successfully utilized with certain salmon species. Several drop-barriers were constructed in Washington, in particular at the Kalama River fishway, Baker River project, Mayfield Dam, and the Cowlitz River Salmon Hatchery (Figs. 1 and 2).

Drop-barrier dams utilized the Ambursen principle (Burroughs 1970), with a free-falling nappe (sheet of water leaving the crest of the dam). Fish that swim or fall through the nappe while attempting to jump the barrier enter an area under the nappe which is usually connected to a side entrance of a fishway. The barrier is usually placed on an angle to the stream, which, in combination with the side-entrance flow, induces along-barrier directional current. The downstream-directed fishway entrance is usually placed as far upstream as possible, where it will still provide good flow conditions downstream from the entrance.

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[1] English measurements were converted to metric units for this report.

The velocity-barrier dam apparently originated at the Coleman Hatchery on the Sacramento River in 1949, where it replaced the picket-rack barrier, which was a constant maintenance problem. Since debris was the primary problem, a barrier that did not strain the flow was desirable. Also, a dam with sufficient drop to prevent fish passage was topographically not feasible. Observations of fish behavior at an old California mining diversion dam of a similar design led to the concept of the velocity-barrier dam at the Coleman Hatchery.

To prevent fish passage at low dams about 0.91 to 1.22 m high, the velocity-barrier dam incorporates a shallow, high-velocity flow over an apron at the base of the dam and a vertical flow (nappe) over the face of the dam. Fish that negotiate the high-velocity flow on the apron must still ascend the vertical-flowing nappe. Since there is no appreciable depth for fish to reorient their position, they are unable to jump or swim up the nappe and pass over the dam. Any cross-positioning of fish to the flow sweeps them off the apron.

The original design had a relatively shallow depth on the apron (about 0.15 m). Where it was not economically justifiable to widen a structure to maintain the 0.15 m depth, the dam height was increased to attain higher apron velocities. This was done at the Fall Creek project in Oregon, where the dam height was increased to 1.6 m; when depth on the apron exceeded 0.15 m, velocities on the apron exceeded 6.1 m/s. With increasing discharge, the nappe of the overflow attained a somewhat flatter angle. However, since the head on the dam increased faster than the depth on the apron, and velocity increased correspondingly, it was believed that an absolute fish block occurred.

Usually the velocity-barrier dams were connected to an entrance to a fishway. Often a side entrance was provided under the flow from the apron, with the downstream wall terminating at the maximum height of the hydraulic jump created below the apron.

Velocity barriers of this type were constructed on the Trinity and Feather Rivers in California, at Falls Creek Dam in the Willamette River Basin, at the Carmen-Smith project on the McKenzie River in Oregon, and at a temporary site at Dworshak Dam in Idaho (Figs. 3 and 4). Each barrier dam differed in design details, primarily because of varying river flows.

Based on test data and experience developed from completed velocity-barrier dams, the Columbia Fisheries Program Office (CFPO) (Portland, Oregon) established the following tentative criteria for velocity-barrier design in August 1967: about 0.15 m flow depth on the apron, 4.9 m/s minimum apron velocity, not less than 4.6 m apron length, about 1.07 m dam height, and tailwater not exceeding the water level at the end of the apron. Ventilation should be provided under the nappe of the flow over the dam to maintain near-atmospheric pressure.

By the late 1960s, several more barrier dams had been designed by CFPO staff. In addition, with the Snake River compensation hatcheries scheduled for completion in the late 1970s and early 1980s, there was further need for such dams. Therefore, firm criteria were needed for velocity-barrier dams that would effectively block passage of adult salmonids. This report describes the design criteria and how they were developed.

METHODS AND MATERIALS

To determine the design criteria, we tested various velocity-barrier dam configurations at the Fisheries Engineering Research Laboratory at Bonneville Dam on the Columbia River (Collins and Elling 1960) during September and October 1969. The main feature of the laboratory was an enclosed rectangular flume 54.9 m long, 7.3 m wide, and 7.3 m deep, located adjacent to the Washington shore fish ladder on the north bank of the Columbia River. Fish were diverted from the primary fish ladder and observed as they passed on their own volition through experimental conditions in the flume. Fish entered the experimental area through a submerged release box, where an observer ascertained species and size. Fish were not handled at any time.

To test various velocity-barrier dam configurations, the flume was set up as shown in Figure 5. The velocity-barrier dam consisted of a dam constructed of stop logs stacked to the desired height in combination with a 1.5 by 4.6 m long apron with a 0.154-m drop over its length. The downstream end of the apron was placed 1.5 m above the floor of the flume to enable testing the effects of varying water levels in the introduction pool on fish passage. The entire structure was constructed of wood and painted brown. Mercury vapor lights (1,000 watt) spaced at 1.8-m intervals 1.8 m above the water provided a total artificial illumination comparable to the natural illumination experienced in the main Bonneville Dam fishway on a bright, cloudy day. Air vents were placed in the side walls between the dam and the nappe to maintain near-atmospheric pressure. A short channel in combination with an 11 m long Denil steeppass fishway (Ziemer 1962; Slatick 1975) placed at a 34% slope provided a bypass fishway.

A water supply system capable of adding up to 60.96 m^3/s of water through a floor diffuser in the exit pool and 6.10 m^3/s of water through the exit fishway was used to regulate the height of the water (the head) over the dam. A drain valve at the lower end of the flume regulated the water level in the introduction pool. Because of the location of the test facility in the flume, the maximum vertical height of the barrier dam and head was limited to 1.83 m.

Our test procedure was to admit salmonids into the introduction pool until a minimum of 20 chinook salmon had entered. The admission of fish was then stopped, and 1 h was allowed for the fish to pass through the test area. This arbitrary time limit was established so excessive time would not be spent waiting for fish to pass through the test area. At the conclusion of each test, the bypass channel was opened allowing fish remaining in the test area free passage out of the test facility. A time-event recorder was used to log fish passage through the test area. Observers at the release and exit points activated push buttons to transmit information to the recorder.

Our experiment consisted of two series of tests. The first evaluated the velocity-barrier dam as a complete block to adult salmonids. The second evaluated the velocity-barrier dam as a complete block to salmonids when they were provided with an alternate bypass route (a Denil fishway) simulating a collection system. In each series, various combinations of head (range 0.3 to 1.22 m) and dam heights (range 0.38 to 1.22 m) were tested. Each combination was tested with the water level of the introduction pool 0.3 m below the apron of the velocity barrier and with the water level even with the apron (Fig. 6).

Tests were evaluated by comparing the percentage of fish admitted into the test area that did not pass over the barrier dam.

RESULTS

Velocity-Barrier Dam as a Complete Block to Fish Passage

A total of 15 combinations of head and dam heights using 1,670 fall-run adult salmonids--861 chinook salmon (O. tshawytscha), 496 coho salmon (O. kisutch), and 313 steelhead--were tested to determine criteria for a complete block of fish passage at a velocity-barrier dam. One hundred percent of the fish were blocked by conditions produced by a 0.91 m high dam with a 0.3 m head (Fig. 7). When the head on the dam was increased to 0.61 m, a few fish were able to swim up the nappe and over the dam. This condition was a block to 94% of the fish tested. Raising the dam height to 1.22 m while maintaining a 0.61 m head again created a complete block to fish passage.

Velocity-Barrier Dam with a Bypass Fishway

When the Denil fishway was used with the velocity-barrier dam, effective blocks were created at lower dam heights. A 0.61 m high dam with a 0.3 m head was a complete block to chinook salmon and blocked 98% of the coho salmon and 94% of the steelhead (Table 1). About 67% of the chinook salmon, 98% of the coho salmon, and 94% of the steelhead ascended the Denil fishway during the test period.

Changing the water level in the introduction pool in relation to the apron was quite effective in causing the fish to bypass the dam. Generally, larger percentages of fish passed through the Denil fishway when the water surface in the introduction pool was 0.3 m below the level of the apron than when the water surface was level with the apron (Table 1).

DISCUSSION AND RECOMMENDATIONS

The velocity-barrier dam was originally developed for installations where height was a limiting design factor. Therefore, the goal of our study was to determine design criteria for a minimum height installation (both structural and head) that would effectively block passage of adult salmonids. The components of this type barrier that are important in blocking fish are height of the dam, water flow over the dam face (nappe), and a shallow, high-velocity flow at the base of the dam.

Although high-velocity flows from the apron plunged or streamed into the introduction pool, underwater flow conditions at the base of the apron were such that, starting approximately 0.3 m below the water surface, water movement was quite slow and had reverse currents (Appendix).

The underwater behavior of fish as they approached the apron was observed from a submerged viewing chamber (Fig. 5). The following description of the behavior of salmon and steelhead attempting to negotiate a velocity-barrier dam may be of value for future design and installation of this type of fish barrier. As fish approached the barrier dam, the majority swam to within about a meter of the downstream end of the apron. Prior to attempting to negotiate the flow from the apron, many fish appeared to examine the structure either by holding and looking at the apron area or swimming along the face of the apron. A number of fish also raised their heads above the water surface. When preparing an attempt at the barrier, a fish would assume a typical exit position (Slatick 1975). The fish would position themselves within 0.3 to 0.61 m of the water surface at approximately a 45° angle facing the flow. After a relatively short period of time, the fish would leap or swim onto the apron of the velocity barrier by simply flexing its body from a stationary position. Very few fish used a moving start to jump onto the apron.

Observations of fish as they attempted to negotiate the velocity-barrier dam indicated that the shallow high velocities generated, up to 5.2 m/s, did not prevent most salmonids from swimming the entire length of the apron. Weaver (1963) demonstrated that some chinook salmon and steelhead can swim against a 4.9-m/s velocity for a distance of at least 25.9 m. Many fish that negotiated the flows on the apron passed through the nappe and rested for a while in the space between the nappe and the dam before returning back down the apron.

The shallow, high-velocity flow prevented fish swimming up the apron from jumping at the vertical flow over the face of the dam. Fish that passed over the barrier dam had to swim up the nappe and over the crest of the dam. It appeared that the depth of the nappe as it struck the apron, in relation to the size of the fish, was the determining factor whether or not it was possible for the fish to swim up the nappe. Figures 8 and 9 illustrate the depth of flow on the apron and relative position of the nappe as it struck the apron at the 0.91 and 1.22 m high barrier dams.

The number of attempts fish made to negotiate the barrier dam declined drastically when the bypass fishway was used in conjunction with the barrier dam. Generally, after attempting the barrier dam at least once, the fish swam around the introduction pool near the base of the apron and the entrance to the bypass channel and eventually became exposed to the lower flows from the Denil fishway (0.16 m^3/s from the Denil and up to 1.83 m^3/s from the apron) located a short distance up the bypass channel.

Our tests indicated that a relatively low, 0.91 to 1.22 m, barrier dam in combination with a 4.6-m long apron with a 0.154-m drop over its length effectively blocked upstream passage of adult salmon and steelhead when operated with a 0.3 to 0.61 m head. In a situation where the fish are to be diverted or collected and a complete fish block is not a requirement, a 0.61 m high-velocity barrier dam operated with a 0.3 m head and a bypass fishway can be over 90% effective.

The effectiveness of a velocity-barrier dam depends on: 1) dam height; 2) head on the dam--which determines the depth of the nappe as it strikes the apron; 3) a shallow, high-velocity flow on the apron; and 4) tailwater never exceeding the water level at the end of the apron. With the knowledge of the time of fish migration, river flow range during the fish migration period, and the stream stage curve, the necessary height and width of the structure can be determined. The dam can be removed for periods when fish are not running, should it be found desirable to maintain a lower water level above the velocity barrier.

Based on our observations of fish behavior, the collection efficiency of a bypass fishway can be substantially increased over the design used in our experiments by incorporating the following changes (Fig. 10): 1) placing the apron of the barrier dam diagonally across the watercourse to form a natural lead, 2) incorporating a fish transportation channel under the end of the apron, 3) placing a fish transportation channel between the nappe and the base of the dam to take advantage of the tendency of fish that swim up the apron proceeding through the nappe, and 4) maintaining sufficient velocity from the bypass collection channel to provide a good directional transport cue for the fish.

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APPENDIX

Water Velocity Measurement Tables and Related Figure

Table 1.--Proportions of chinook salmon, coho salmon, and steelhead which passed over the barrier dam and ascended the Denil fishway or remained in the introduction pool under various test conditions.

Species	Test conditions		Number of fish entered	Passed over barrier dam	Ascended Denil	Remained in intro pool
	Head (m)	Dam (m)	No.	%	%	%
Tailwater 0.3 m below apron						
Chinook salmon	0.30	0.38	43	51.2	41.8	7.0
	0.30	0.61	60	0.0	66.7	33.3
	0.30	0.91	32	0.0	90.6	9.4
	0.30	1.22	23	0.0	60.9	39.1
	0.61	0.91	28	0.0	42.8	57.2
	0.61	1.22	20	0.0	55.0	45.0
Coho salmon	0.30	0.38	53	32.1	49.1	18.8
	0.30	0.61	47	2.1	97.9	0.0
	0.30	0.91	49	0.0	81.6	18.4
	0.30	1.22	26	0.0	100.0	0.0
	0.61	0.91	44	4.5	90.9	4.6
	0.61	1.22	15	0.0	46.7	53.3
Steelhead	0.30	0.38	7	42.8	42.8	14.4
	0.30	0.61	16	6.3	93.7	0.0
	0.30	0.91	13	0.0	69.2	30.8
	0.30	1.22	22	0.0	100.0	0.0
	0.61	0.91	22	4.5	40.9	54.6
	0.61	1.22	14	0.0	64.3	35.7
Tailwater even with apron						
Chinook salmon	0.30	0.91	233	0.0	51.1	48.9
	0.30	1.22	239	9.9	44.8	55.2
	0.61	0.91	143	7.7	28.7	63.6
	0.61	1.22	42	0.0	19.0	81.0
Coho salmon	0.30	0.91	45	0.0	100.0	0.0
	0.30	1.22	42	0.0	100.0	0.0
	0.61	0.91	13	0.0	53.8	45.2
	0.61	1.22	3	0.0	33.3	66.7
Steelhead	0.30	0.91	30	0.0	56.7	43.3
	0.30	1.22	30	0.0	66.7	33.3
	0.61	0.91	30	6.7	23.3	70.0
	0.61	1.22	4	0.0	25.0	75.0

FIGURE CAPTIONS

Figure 1.--Cross section of two drop-barrier dams used to collect Pacific salmon in Washington: Kalama River Fishway (top) and Baker River project (bottom).

Figure 2.--Cross section of drop-barrier dam used to collect Pacific salmon at Mayfield Dam on the Cowlitz River, Washington.

Figure 3.--Cross section of velocity-barrier dam used to collect Pacific salmon at the Carmen-Smith project on the McKenzie River, Oregon.

Figure 4.--Cross section of two velocity-barrier dams used to collect Pacific salmon: Feather River Hatchery interim facilities, California (top) and Fall Creek Dam in the Willamette River Basin, Oregon (bottom).

Figure 5.--Plan view of setup used for tests with the velocity-type barrier dam. Side view shows the principal features of the velocity-barrier dam.

Figure 6.--Top--the velocity-barrier dam operating with a 0.91-m dam, a 0.3-m head, and the water level of the introduction pool at 0.3-m below the apron. Bottom--identical operation except the water level of the introduction pool is even with the apron.

Figure 7.--Proportion of fish blocked by the velocity-barrier dam under various dam heights, head (height of flow over dam), and the average m/s velocity on the end of apron.

Figure 8.--Side view of the 0.91-m high velocity-barrier dam with a 0.30- and 0.61-m head and the tailwater even with and below the apron illustrating the depth of flow (cm) on the apron, relative position of the nappe as it strikes the apron, and average m/s velocity at the downstream end of the apron.

Figure 9.--Side view of the 1.22-m high velocity-barrier dam with a 0.30- and 0.61-m head and the tailwater even with and below the apron illustrating the depth of flow (cm) on the apron, relative position of the nappe as it strikes the apron, and the average m/s velocity at the downstream end of the apron.

Figure 10.--Isometric view of proposed velocity-barrier dam and locations of fish collection channels.

Appendix Table 1.--Water velocity measurements at the velocity-barrier dam with a 0.3-m head, a 0.61-m dam, and the water level below the apron, operated in conjunction with a Denil steeppass fishway, 6 November 1969.

Head 0.3 m Denil slope 34%
Dam 0.61 m

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.121	0.127	0.111	0.102

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.079	0.098	0.105	
Velocity (m/s)	3.627	3.993	3.901	(Average 3.84 m/s)

Denil bypass channel

Station number	4	5	6
Water depth (m)	1.172	1.175	1.178
Velocity at 0.91 m above floor (m/s)	0.549 ↓	0.488 ↓	0.427 ↓
Velocity at 0.61 m above floor (m/s)	0.823 ↙	0.762 ↓	0.610 ↓
Velocity at 0.30 m above floor (m/s)	0.579 ↙	0.823 ↓	0.671 ↓

Introduction pool

Station number	7	8	9	10
Water depth (m)	1.191	1.194	1.197	1.197
Velocity at 0.91 m above floor (m/s)	0.427 ↘	0.427 ↓	0.396 ↶	1.006 ↓
Velocity at 0.61 m above floor (m/s)	0.640 ↘	0.305 ↓	0.183 ↕↘	0.244 ↙↕
Velocity at 0.30 m above floor (m/s)	0.640 ↘	0.427 ↓	0.213 ↕↘	0.183 ↘↙

Station number	11	12	13	14	15
Water depth (m)	1.213	1.207	1.207	1.194	1.194
Velocity at 0.91 m above floor (m/s)	2.103 ↓	1.798 ↓	1.402 ←↓	0.122 ↻	0.366 ↖
Velocity at 0.61 m above floor (m/s)	0.183 ↓	0.274 ↓	0.792 ↓	0.213 ↻	0.366 ↖
Velocity at 0.30 m above floor (m/s)	0.183 ↘↙	0.213 ↖↕	0.366 ↖	0.396 ↖	0.396 ↖

Flow direction: upstream = ↑ ; downstream = ↓ .

Metric units have been converted from English units.

Appendix Table 2.--Water velocity measurements at the velocity-barrier dam with a 0.3-m head, a 0.61-m dam, and the water level even with the apron, operated in conjunction with a Denil steeppass fishway, 3 December 1969.

Head 0.3 m Denil slope 30%
Dam 0.61 m

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.108	0.102	0.089	0.086

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.067	0.079	0.070	
Velocity (m/s)	3.475	3.810	3.901	(Average 3.719 m/s)

Denil bypass channel

Station number	4		5		6	
Water depth (m)	1.597		1.588		1.588	
Velocity at 1.52 m above floor (m/s)	0.671	↘	0.640	↕↘	0.671	↕↘
Velocity at 1.22 m above floor (m/s)	0.213	↓	0.183	↕→	0.213	↕→
Velocity at 0.91 m above floor (m/s)	0.183	↓	0.122	↘	0.191	↓
Velocity at 0.61 m above floor (m/s)	0.122	↓	0.152	↓	0.061	↙
Velocity at 0.30 m above floor (m/s)	0.061	↘	0.091	↓	0.091	↓

Introduction pool

Station number	7		8		9		10	
Water depth (m)	1.591		1.591		1.597		1.632	
Velocity at 1.52 m above floor (m/s)	0.488	↓	0.457	↘	0.488	↘	2.195	↓
Velocity at 1.22 m above floor (m/s)	0.152	↓	0.061	↓	0.122	↓	0.549	↓
Velocity at 0.91 m above floor (m/s)	0.061	↓	0.061	↓	--		0.122	→
Velocity at 0.61 m above floor (m/s)	0.091	↓	--		--		0.091	→
Velocity at 0.30 m above floor (m/s)	0.061	↓	0.061	↓	--		0.122	↗

Station number	11		12		13		14		15	
Water depth (m)	1.708		1.708		1.711		1.695		1.626	
Velocity at 1.52 m above floor (m/s)	1.951	↓	1.554	↓	1.646	↓	1.311	↓	0.061	↘
Velocity at 1.22 m above floor (m/s)	0.213	↕↘	0.061	↔↘	0.091	↙→	0.274	↗→	0.061	↙↘
Velocity at 0.91 m above floor (m/s)	0.122	↗	0.122	→	0.122	→	0.091	↑	0.091	↓
Velocity at 0.61 m above floor (m/s)	0.091	↗	0.061	↗	0.061	↗	0.061	↗	0.183	↖
Velocity at 0.30 m above floor (m/s)	0.122	→	0.091	→	0.122	→	0.091	↗	0.183	↖

Flow direction: upstream = ↑ ; downstream = ↓.

Metric units have been converted from English units.
--Flow too low to record with Hoff* meter. *Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

Appendix Table 3.--Water velocity measurements at the velocity-barrier dam with a 0.3-m head, a 0.91-m dam, and the water level below the apron, operated in conjunction with a Denil steeppass fishway, 7 November 1969.

Head 0.3 m Denil slope 34%
Dam 0.91 m

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.076	0.108	0.171	0.111

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.060	0.064	0.064	
Velocity (m/s)	3.383	3.901	4.206	(Average 3.81 m/s)

Denil bypass channel

Station number	4		5		6	
Water depth (m)	1.187		1.191		1.194	
Velocity at 0.91 m above floor (m/s)	0.274	[illegible]	0.366	↓	0.518	↓
Velocity at 0.61 m above floor (m/s)	0.884	↙	0.488	↓	0.579	↓
Velocity at 0.30 m above floor (m/s)	0.640	↙	0.549	↓	0.671	↓

Introduction pool

Station number	7		8		9		10		15	
Water depth (m)	1.191		1.191		1.191		1.210			
Velocity at 0.91 m above floor (m/s)	0.457	↙	0.244	↙	0.396	↺	2.408	↓		
Velocity at 0.61 m above floor (m/s)	0.548	↙	0.305	↙	0.152	↙	0.152	[illegible]		
Velocity at 0.30 m above floor (m/s)	0.671	↓	0.335	↓	0.152	↙	0.152	↖		
Station number	11		12		13		14		15	
Water depth (m)	1.235		1.226		1.235		1.197		1.197	
Velocity at 0.91 m above floor (m/s)	1.920	↓	1.707	↓	1.585	↓	0.366	↻	0.183	←
Velocity at 0.61 m above floor (m/s)	0.152	[illegible]	0.152	[illegible]	0.244	[illegible]	0.213	[illegible]	0.274	←
Velocity at 0.30 m above floor (m/s)	0.152	↖	0.183	[illegible]	0.152	↖	0.335	↖	0.366	←

Flow direction: upstream = ↑ ; downstream = ↓ .

Metric units have been converted from English units.

Appendix Table 4.--Water velocity measurements at the velocity barrier-dam with a 0.3-m head, a 0.91-m dam, and the water level even with the apron, operated in conjunction with a Denil steeppass fishway, 4-5 December 1969.

Head 0.3 m
Dam 0.91 m

Denil slope 30%

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.130	0.124	0.203	0.127

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.079	0.092	0.086	
Velocity (m/s)	3.566	3.810	4.206	(Average 3.871 m/s)

Denil bypass channel

Station number	4	5	6
Water depth (m)	1.578	1.568	1.581
Velocity at 1.52 m above floor (m/s)	0.732 ↘	0.792 ↙↘	0.762 ↙
Velocity at 1.22 m above floor (m/s)	0.213 ↓	0.091 ↓	0.274 ↓
Velocity at 0.91 m above floor (m/s)	0.213 ↓	0.091 ↓	0.091 ↓
Velocity at 0.61 m above floor (m/s)	0.091 ↓	0.122 ↓	0.091 ↓
Velocity at 0.30 m above floor (m/s)	0.091 ↓	0.152 ↓	0.152 ↓

Introduction pool

Station number	7	8	9	10	
Water depth (m)	1.588	1.588	1.591	1.676	
Velocity at 1.52 m above floor (m/s)	0.488 ↓	0.457 ↓	0.488 ↙	2.256 ↓	
Velocity at 1.22 m above floor (m/s)	0.152 ↘	0.061 ↘	0.152 ↓	0.244 ↓↘	
Velocity at 0.91 m above floor (m/s)	0.061 ↓	--	0.061 ↓	0.061 ↖	
Velocity at 0.61 m above floor (m/s)	0.061 ↓	--	0.091 ←	0.061 ↖	
Velocity at 0.30 m above floor (m/s)	0.122 ↓	--	0.061 ↓	0.061 ↗	
Station number	11	12	13	14	15
Water depth (m)	1.721	1.724	1.680	1.641	1.616
Velocity at 1.52 m above floor (m/s)	1.829 ↓	1.707 ↓	1.676 ↓	0.975 ↓	0.152 ↓
Velocity at 1.22 m above floor (m/s)	0.213 ↓→	0.244 ↑	0.183 ↑	0.122 ↘	0.152 ↓
Velocity at 0.91 m above floor (m/s)	0.091 ↖	0.152 ↖	0.152 ↖	0.183 ↖	0.213 ←
Velocity at 0.61 m above floor (m/s)	0.122 ↖	0.061 ↑	0.061 ↑	0.122 ↑	0.244 ↖
Velocity at 0.30 m above floor (m/s)	--	0.091 ↗	--	0.061 ↗	0.152 ↑

Flow direction: upstream = ↑ ; downstream = ↓ .

Metric units have been converted from English units.
--Flow too low to record with Hoff meter.

Appendix Table 5.--Water velocity measurements at the velocity barrier-dam with a 0.61-m head, a 0.91-m dam, and the water level below the apron, operated in conjunction with a Denil steeppass fishway, 6 November 1969.

Head 0.61 m
Dam 0.91 m

Denil slope 34%

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.241	0.311	0.249	0.749

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.197	0.191	0.197	
Velocity (m/s)	4.663	4.938	4.938	(Average 4.846 m/s)

Denil bypass channel

Station number	4	5	6
Water depth (m)	1.140	1.146	1.146
Velocity at 0.91 m above floor (m/s)	0.488 ↘	0.518 ↓	0.244 ↓
Velocity at 0.61 m above floor (m/s)	0.823 ↓	0.762 ↓	0.701 ↓
Velocity at 0.30 m above floor (m/s)	0.732 ↓	0.914 ↓	0.732 ↓

Introduction pool

Station number	7	8	9	10	
Water depth (m)	1.165	1.165	1.172	1.175	
Velocity at 0.91 m above floor (m/s)	0.488 ↘	0.792 ↘	0.549 ↓	3.292 ↓	
Velocity at 0.61 m above floor (m/s)	0.610 ↓	0.396 ↓	0.183 ↻	0.244 ↻	
Velocity at 0.30 m above floor (m/s)	0.762 ↓	0.792 ↻	0.213 ↓	0.274 ↖	
Station number	11	12	13	14	15
Water depth (m)	1.165	1.168	1.168	1.191	1.184
Velocity at 0.91 m above floor (m/s)	3.383 ↓	2.987 ↓	3.109 ↓	2.134 ↓	0.305 ←
Velocity at 0.61 m above floor (m/s)	0.213 ↻	0.244 ↻	0.488 ↓	0.488 ↻	0.366 ←
Velocity at 0.30 m above floor (m/s)	0.305 ↻	0.549 ↻	0.488 ↻	0.488 ←	0.396 ←

Flow direction: upstream = ↑ ; downstream = ↓ .

Metric units have been converted from English units.

Appendix Table 6.--Water velocity measurements at the velocity-barrier dam with a 0.61-m head, a 0.91-m dam, and the water level even with the apron, operated in conjunction with a Denil steeppass fishway, 5 and 12 December 1969.

Head 0.61 m Denil slope 30%
Dam 0.91 m

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.203	0.238	0.222	0.686

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.171	0.197	0.171	
Velocity (m/s)	4.846	5.090	4.968	(Average 4.968 m/s)

Denil bypass channel

Station number	4		5		6	
Water depth (m)	1.724		1.727		1.734	
Velocity at 1.52 m above floor (m/s)	0.396	↘	0.396	↓	0.488	↙
Velocity at 1.22 m above floor (m/s)	0.152	↘	0.152	↘	0.244	↓
Velocity at 0.91 m above floor (m/s)	0.183	↘	0.091	↘	0.152	↓
Velocity at 0.61 m above floor (m/s)	0.091	↘	0.152	↓	0.122	↓
Velocity at 0.30 m above floor (m/s)	0.183	↓	0.152	↓	--	

Introduction pool

Station number	7		8		9		10	
Water depth (m)	1.727		1.727		1.772		1.829	
Velocity at 1.52 m above floor (m/s)	0.366	↓	0.244	↓	0.701	↓	2.896	↓
Velocity at 1.22 m above floor (m/s)	0.213	↓	0.091	↓	0.122	↓	0.366	↓
Velocity at 0.91 m above floor (m/s)	0.061	↙	0.091	↓	0.152	↑	0.061	↗
Velocity at 0.61 m above floor (m/s)	0.091	↙	0.091	↓	0.091	↙	0.152	↗
Velocity at 0.30 m above floor (m/s)	0.061	↘	0.061	↓	0.183	↕→	0.091	↑

Station number	11		12		13		14		15	
Water depth (m)	1.807		1.807		1.807		1.829		1.794	
Velocity at 1.52 m above floor (m/s)	3.048	↓	3.536	↓	3.200	↓	1.494	↘	0.122	↘
Velocity at 1.22 m above floor (m/s)	0.396	↓	0.427	↓	0.305	↓	0.122	↓	0.152	↘
Velocity at 0.91 m above floor (m/s)	0.061	↑	0.061	↗	0.122	↗	0.091	↗	0.335	↖
Velocity at 0.61 m above floor (m/s)	0.061	↑	0.213	↗	0.061	↗	0.152	↗	0.152	↗
Velocity at 0.30 m above floor (m/s)	0.122	↑	0.152	↑	0.122	↗	0.152	↑	0.091	↖

Flow direction: upstream = ↑ ; downstream = ↓ .

Metric units have been converted from English units.

Appendix Table 7.--Water velocity measurements at the velocity barrier-dam with a 0.3-m head, a 1.22-m dam, and the water level below the apron, operated in conjunction with a Denil steeppass fishway, 18-19 November 1969.

Head 0.3 m Denil slope 34%
Dam 1.22 m

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.108	0.121	0.260	0.324

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.070	0.089	0.102	
Velocity (m/s)	3.383	3.475	3.840	(Average 3.566 m/s)

Denil bypass channel

Station number	4	5	6
Water depth (m)	1.203	1.203	1.452
Velocity at 0.91 m above floor (m/s)	0.244 ↗↙	0.518 ↕↘	0.549 ↘
Velocity at 0.61 m above floor (m/s)	0.305 ↕→	0.792 ↓	0.640 ↘
Velocity at 0.30 m above floor (m/s)	0.427 ↕→	0.853 ↕↘	0.640 ↘

Introduction pool

Station number	7	8	9	10	
Water depth (m)	1.210	1.210	1.216	1.276	
Velocity at 0.91 m above floor (m/s)	0.640 ↓	0.488 ↓	0.366 ↙↘	2.103 ↕↘	
Velocity at 0.61 m above floor (m/s)	0.701 ↓	0.213 ↘	0.152 ↕↗	0.152 ↕↗	
Velocity at 0.30 m above floor (m/s)	0.762 ↙	0.427 ↓	0.183 →	0.122 ↗	
Station number	11	12	13	14	15
Water depth (m)	1.273	1.194	1.283	1.226	1.210
Velocity at 0.91 m above floor (m/s)	1.859 ↕↘	1.646 ↙↘	1.311 ←↕	0.396 ↻	0.244 ↖
Velocity at 0.61 m above floor (m/s)	0.091 ↕	0.152 ↺	0.122 ↖↘	0.335 ↖	0.335 ↖
Velocity at 0.30 m above floor (m/s)	0.152 ↗	0.213 ↗	0.305 ↗↙	0.183 ↙	0.122 ↙↘

Flow direction: upstream = ↑ ; downstream = ↓.

Metric units have been converted from English units.

Appendix Table 8.--Water velocity measurements at the velocity-barrier dam with a 0.3-m head, a 1.22-m dam, and the water level even with the apron, operated in conjunction with a Denil steeppass fishway, 19-20 November 1969.

Head 0.3 m
Dam 1.22 m

Denil slope 34%

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.102	0.114	0.203	0.432

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.044	0.060	0.083	
Velocity (m/s)	3.475	3.383	4.542	(Average 3.81 m/s)

Denil bypass channel

Station number	4	5	6
Water depth (m)	1.565	1.568	1.584
Velocity at 1.52 m above floor (m/s)	0.579 ↘	0.366 ↘	0.671 ↘
Velocity at 1.22 m above floor (m/s)	0.579 ↓↘	0.305 ↘	0.305 →
Velocity at 0.91 m above floor (m/s)	0.488 →↘	0.518 ↘	0.244 ↓
Velocity at 0.61 m above floor (m/s)	0.305 ↗→	0.457 ↓	0.427 ↓
Velocity at 0.30 m above floor (m/s)	0.396 ↓→	0.671 ↘	0.640 ↘

Introduction pool

Station number	7	8	9	10
Water depth (m)	1.584	1.591	1.603	1.705
Velocity at 1.52 m above floor (m/s)	0.518 ↘	0.610 ↓	0.671 ↓	2.499 ↓
Velocity at 1.22 m above floor (m/s)	0.427 ↓	0.396 ↓	0.396 ↘	0.305 ↓
Velocity at 0.91 m above floor (m/s)	0.610 ↓	0.518 ↓	0.549 ↘	0.122 →
Velocity at 0.61 m above floor (m/s)	0.518 ↓	0.274 ↘	0.122 ↘	0.152 →
Velocity at 0.30 m above floor (m/s)	0.732 ↓	0.579 ↓	0.183 ↘	0.091 →

Station number	11	12	13	14	15
Water depth (m)	1.730	1.715	1.648	1.622	1.600
Velocity at 1.52 m above floor (m/s)	1.707 ↓	1.494 ↓	1.494 ↓	0.457 ↙	0.061 ↘
Velocity at 1.22 m above floor (m/s)	0.122 ↓→	0.152 ↘↗	0.122 →	0.152 ↘	0.152 ↘
Velocity at 0.91 m above floor (m/s)	0.122 →	0.213 ↘	0.213 ↓	0.152 ↓	0.122 ↓
Velocity at 0.61 m above floor (m/s)	0.152 →	0.183 →	0.152 →	0.213 ↘	0.213 ↓
Velocity at 0.30 m above floor (m/s)	0.091 →	0.122 →	0.122 →	0.152 ↘	--

Flow direction: upstream = ↑ ; downstream = ↓.

Metric units have been converted from English units.

Appendix Table 9.--Water velocity measurements at the velocity-barrier dam with a 0.61-m head, a 1.22-m dam, and the water level below the apron, operated in conjunction with a Denil steeppass fishway, 18 November 1969.

Head 0.61 m
Dam 1.22 m

Denil slope 34%

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.260	0.384	0.194	1.048

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.191	0.191	0.191	
Velocity (m/s)	4.755	5.334	5.151	(Average 5.09 m/s)

Denil bypass channel

Station number	4	5	6
Water depth (m)	1.143	1.118	1.156
Velocity at 0.91 m above floor (m/s)	0.366 [illegible]	0.610 ↘	0.610 ↓
Velocity at 0.61 m above floor (m/s)	0.914 ↓	0.762 ↓	0.640 ↘
Velocity at 0.30 m above floor (m/s)	0.762 ↓	0.914 ↓	0.762 ↙

Introduction pool

Station number	7	8	9	10	
Water depth (m)	1.165	1.168	1.200	1.270	
Velocity at 0.91 m above floor (m/s)	0.701 ↓	0.579 ↘	0.427 ↓	2.195 ↓	
Velocity at 0.61 m above floor (m/s)	0.732 ↘	0.396 ↓	0.152 [illegible]	0.183 [illegible]	
Velocity at 0.30 m above floor (m/s)	0.792 ↓	0.488 ↓	0.183 ↓	0.152 ↓	
Station number	11	12	13	14	15
Water depth (m)	1.283	1.191	1.146	1.219	1.178
Velocity at 0.91 m above floor (m/s)	3.048 ↓	2.835 ↓	2.865 ↓	0.152 [illegible]	0.427 ↙
Velocity at 0.61 m above floor (m/s)	0.244 ↓	0.122 [illegible]	0.183 [illegible]	0.152 [illegible]	0.488 [illegible]
Velocity at 0.30 m above floor (m/s)	0.152 ↙	0.213 ↓	0.213 ↙	0.274 [illegible]	0.396 ↙

Flow direction: upstream = ↑ ; downstream = ↓ .

Metric units have been converted from English units.

Appendix Table 10.--Water velocity measurements at the velocity-barrier dam with a 0.61-m head, a 1.22-m dam, and the water level even with the apron, operated in conjunction with a Denil steeppass fishway, 20 November 1969.

Head 0.61 m
Dam 1.22 m

Denil slope 34%

Water depth on apron

Distance from downstream end of apron (m)	0.914	1.829	2.743	3.658
Water Depth on apron (m)	0.260	0.330	0.219	1.057

Water conditions on downstream end of apron

Station number	1	2	3	
Water depth (m)	0.206	0.229	0.171	
Velocity (m/s)	4.877	5.304	5.517	(Average 5.243 m/s)

Denil bypass channel

Station number	4		5		6	
Water depth (m)	1.699		1.692		1.695	
Velocity at 1.52 m above floor (m/s)	0.671	↓	0.427	↓	0.579	↘
Velocity at 1.22 m above floor (m/s)	0.427	↓→	0.213	↙	0.183	↓
Velocity at 0.91 m above floor (m/s)	0.305	→↘	0.396	↓	0.183	↓
Velocity at 0.61 m above floor (m/s)	0.335	↗→	0.488	↘	0.366	↘
Velocity at 0.30 m above floor (m/s)	0.488	↗→	0.701	↓	0.762	↓

Introduction pool

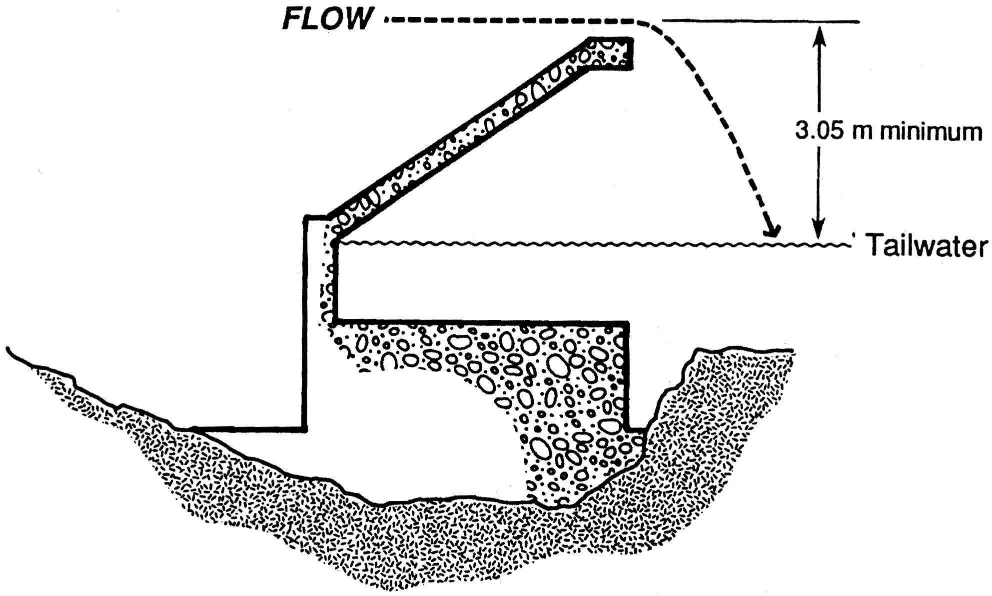
Station number	7		8		9		10	
Water depth (m)	1.727		1.743		1.803		1.816	
Velocity at 1.52 m above floor (m/s)	0.488	↘	0.549	↓	0.732	↙↘	2.408	↓
Velocity at 1.22 m above floor (m/s)	0.366	↙	0.183	↙	0.396	↓	0.213	↺
Velocity at 0.91 m above floor (m/s)	0.366	↓	0.396	↙	0.183	↗	0.122	↑
Velocity at 0.61 m above floor (m/s)	0.518	↘	0.152	↓	0.213	↻	0.091	↗
Velocity at 0.30 m above floor (m/s)	0.762	↓	0.213	↙	0.213	↻	0.152	↑

Station number	11		12		13		14		15	
Water depth (m)	1.778		1.819		1.791		1.838		1.765	
Velocity at 1.52 m above floor (m/s)	2.225	↓	3.322	↓	2.621	↓	2.347	↓	0.183	↓
Velocity at 1.22 m above floor (m/s)	0.396	↙↘	0.335	↙↘	0.231	↓	0.213	↻	0.305	↖
Velocity at 0.91 m above floor (m/s)	0.183	↑	0.122	↑	0.274	↑	0.091	↗	0.122	↙
Velocity at 0.61 m above floor (m/s)	0.091	↑	0.061	↑	0.091	↑	0.061	↑	0.305	←
Velocity at 0.30 m above floor (m/s)	0.122	↑	0.091	↑	0.061	↑	0.091	↑	0.335	↖

Flow direction: upstream = ↑ ; downstream = ↓ .

Metric units have been converted from English units.

Kalama River



Baker River

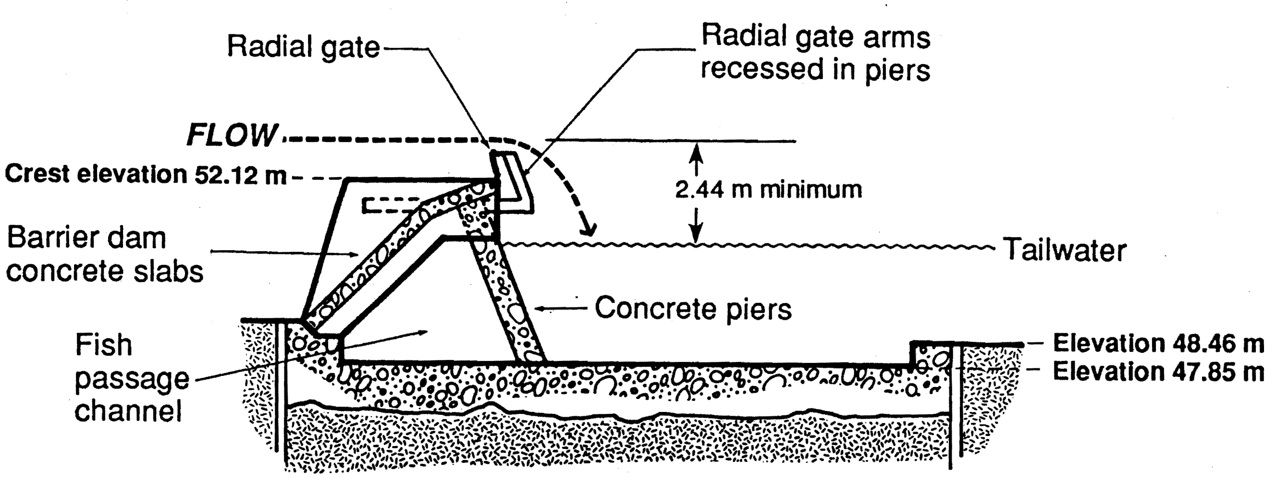


Figure 1.--Cross section of two drop-barrier dams used to collect Pacific salmon in Washington: Kalama River Fishway (top) and Baker River project (bottom).

Cowlitz River

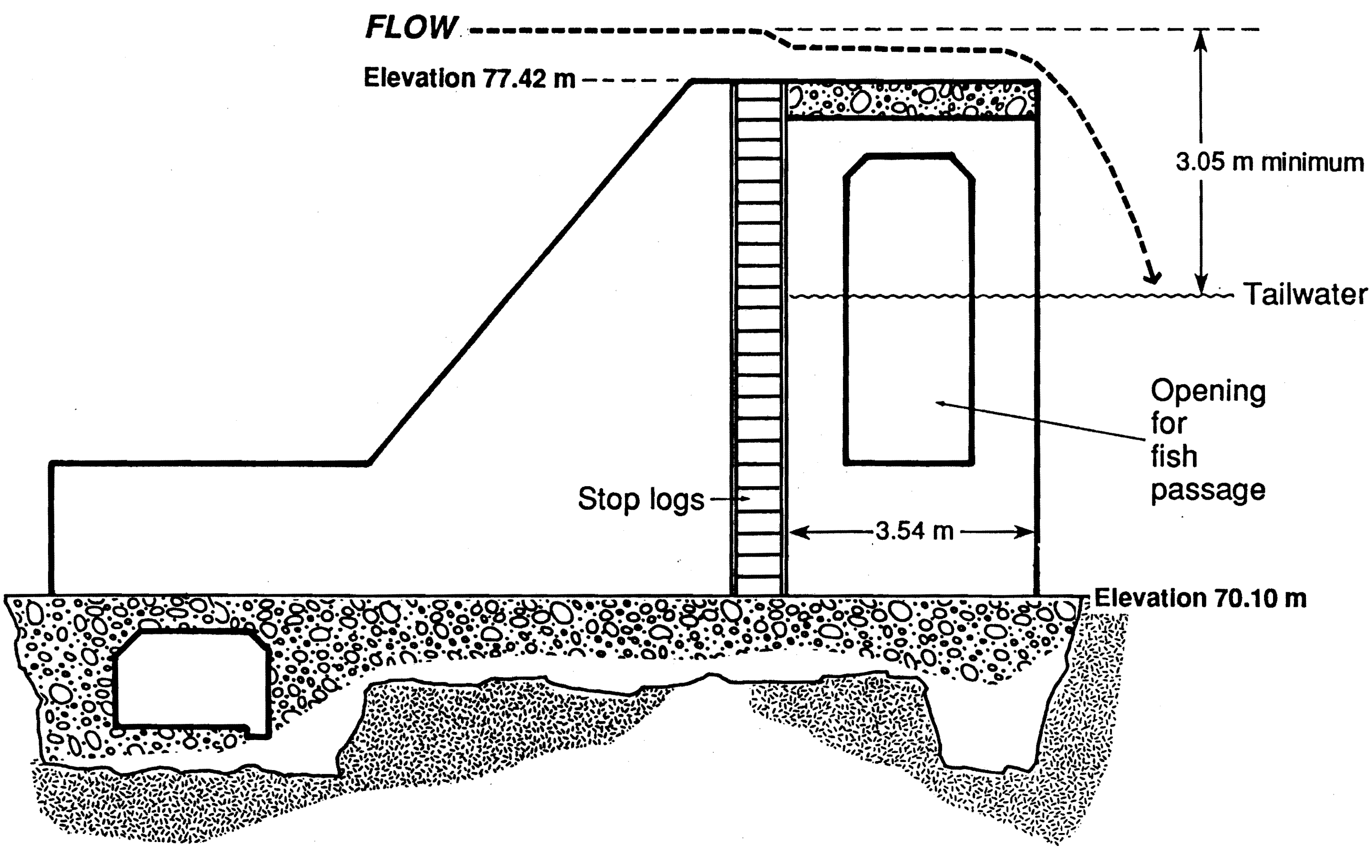


Figure 2.--Cross section of drop-barrier dam used to collect Pacific salmon at Mayfield Dam on the Cowlitz River, Washington.

McKenzie River

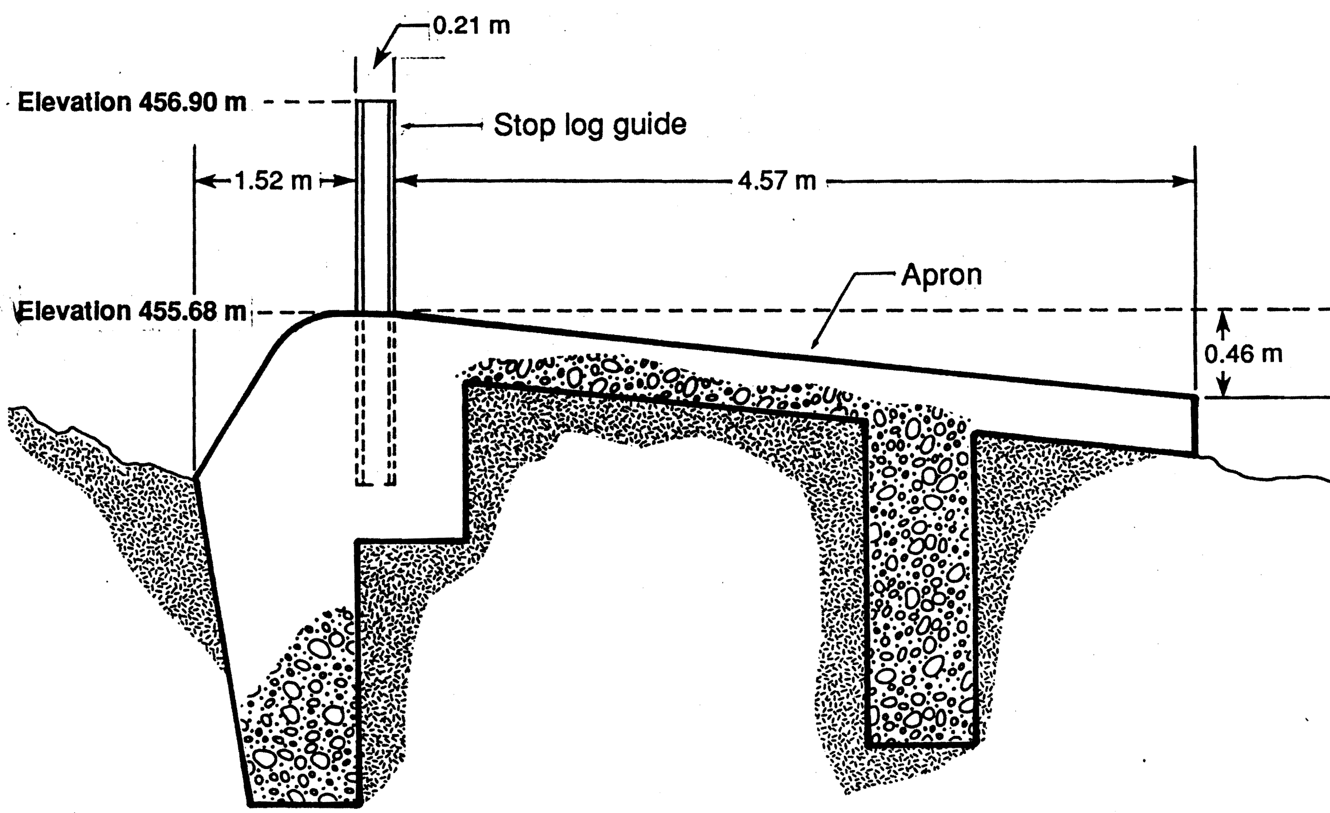
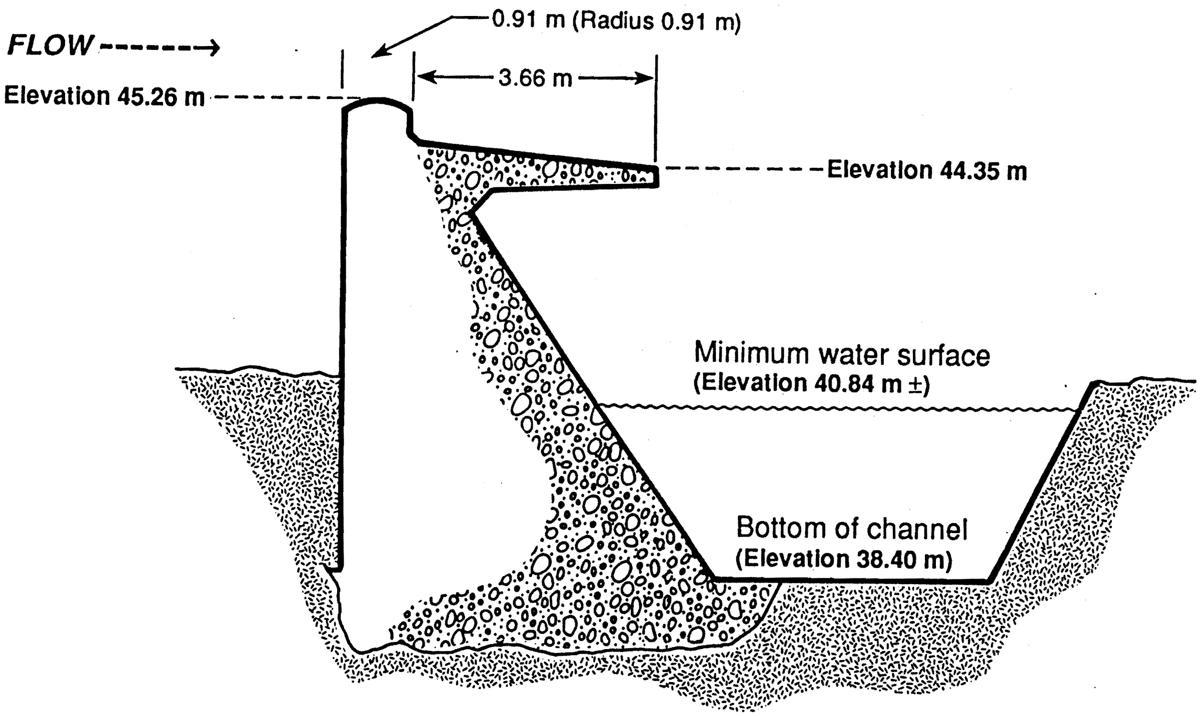


Figure 3.--Cross section of velocity-barrier dam used to collect Pacific salmon at the Carmen-Smith project on the McKenzie River, Oregon.

Feather River



Willamette River Basin

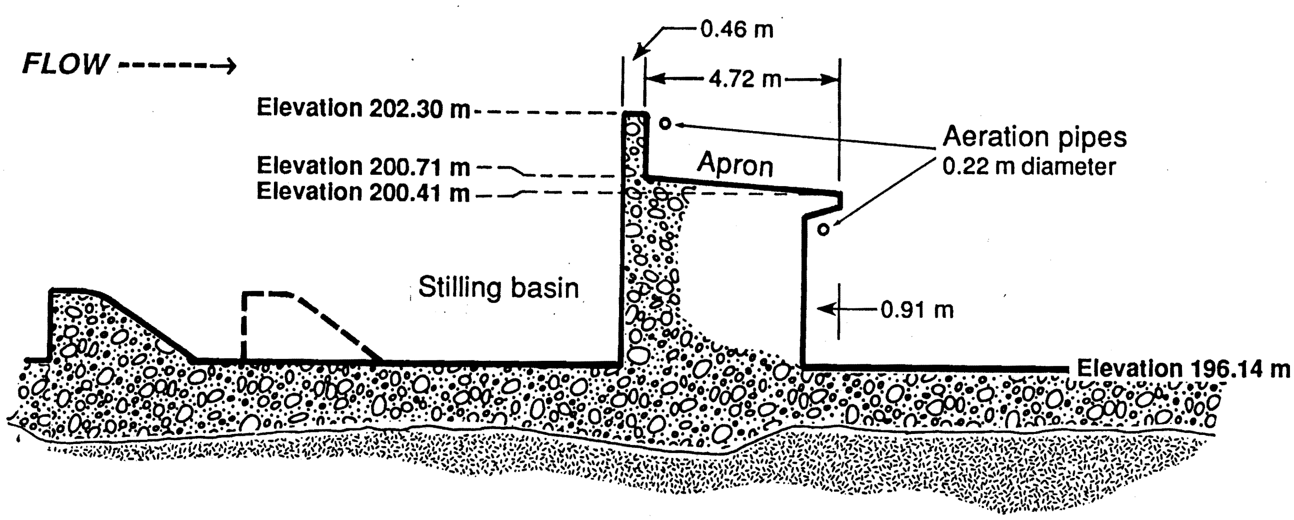
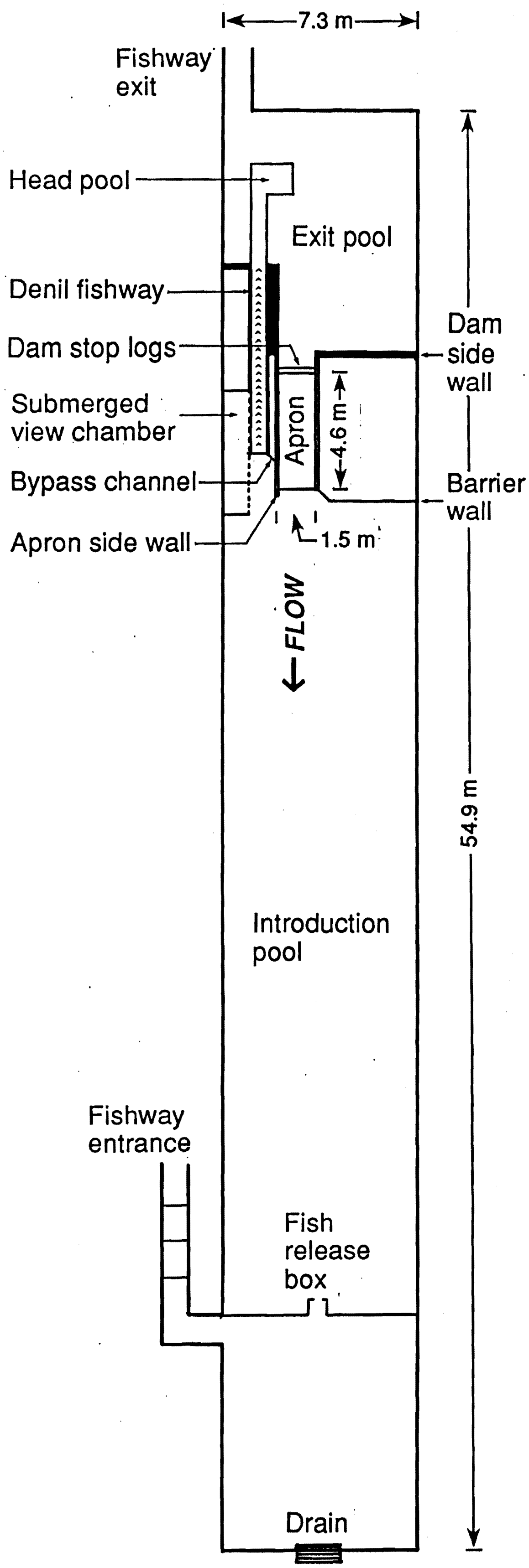
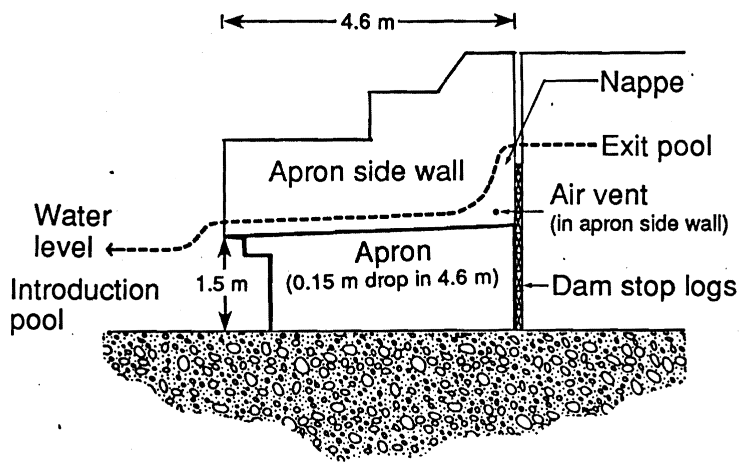


Figure 4.--Cross section of two velocity-barrier dams used to collect Pacific salmon: Feather River Hatchery interim facilities, California (top) and Fall Creek Dam in the Willamette River Basin, Oregon (bottom).



PLAN VIEW



SIDE VIEW

Figure 5.--Plan view of setup used for tests with the velocity-type barrier dam. Side view shows the principal features of the velocity-barrier dam.

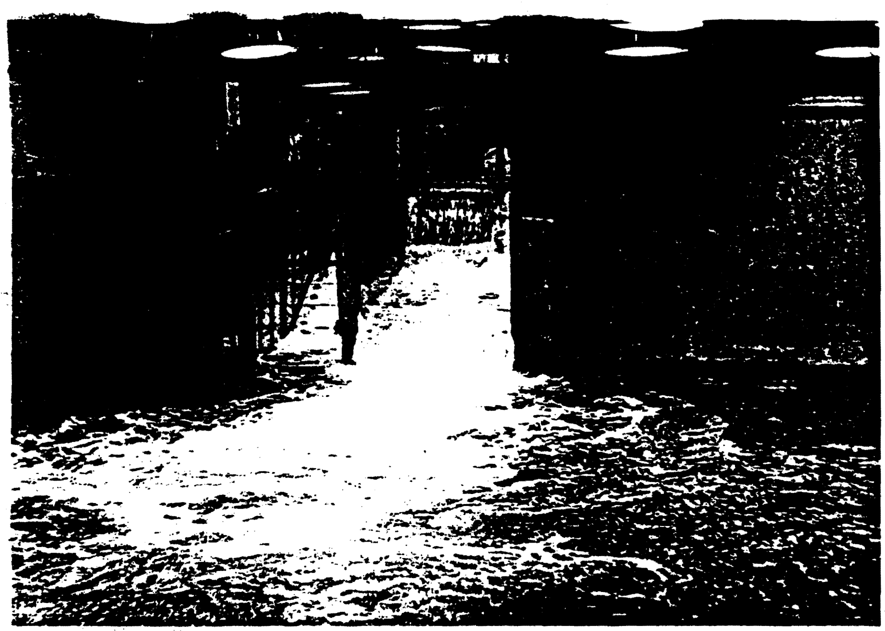


Figure 6.-- View of the velocity-barrier dam operating with a 0.91-m dam, a 0.3-m head, and the water level of the introduction pool at 0.39m below the apron (top). Operations are identical except that the water level of the introduction pool is even with the apron (bottom).

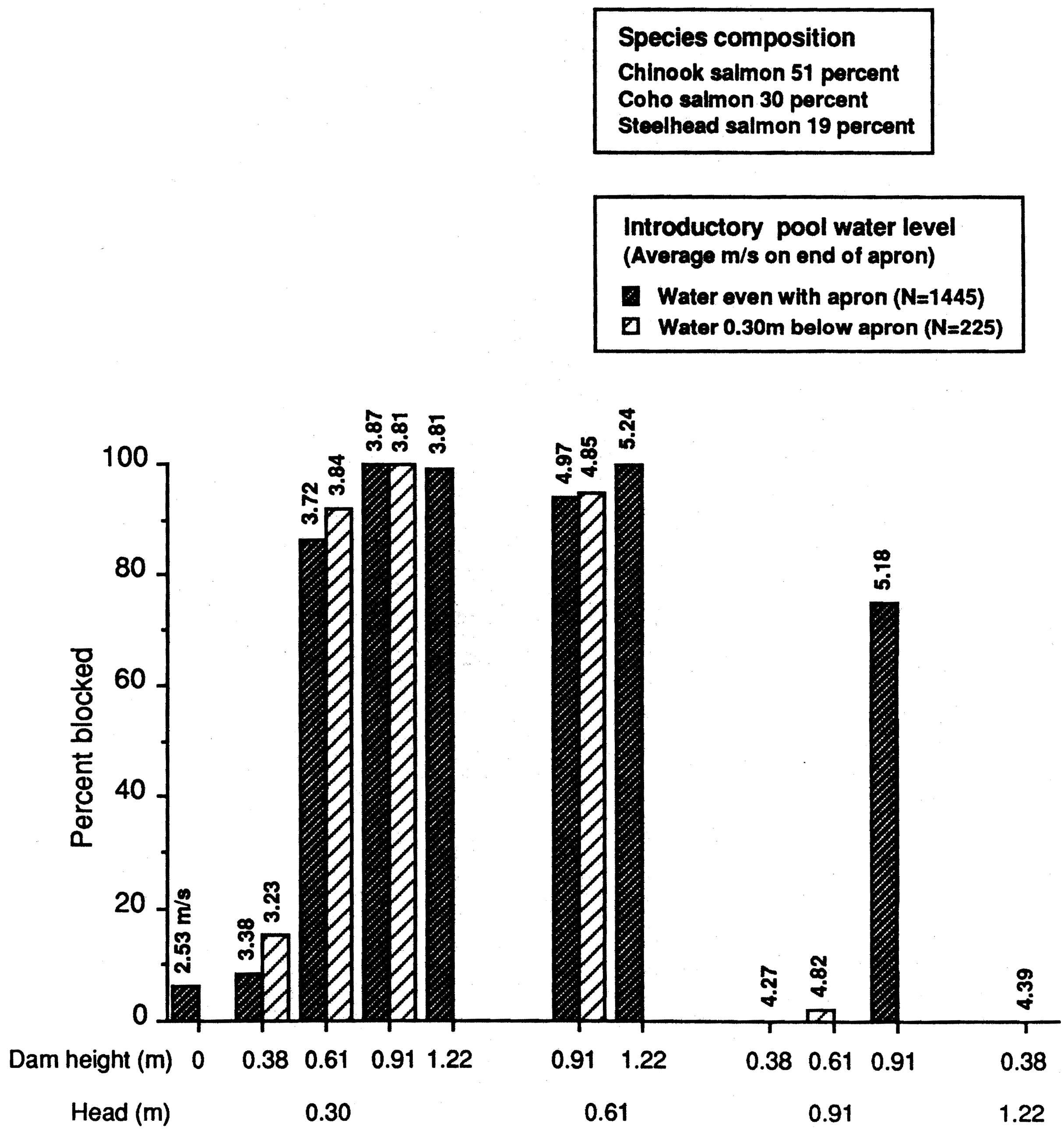


Figure 7.--Proportion of fish blocked by the velocity-barrier dam under various dam heights, head (height of flow over dam), and the average m/s velocity on the end of apron.

0.91 m high velocity barrier dam

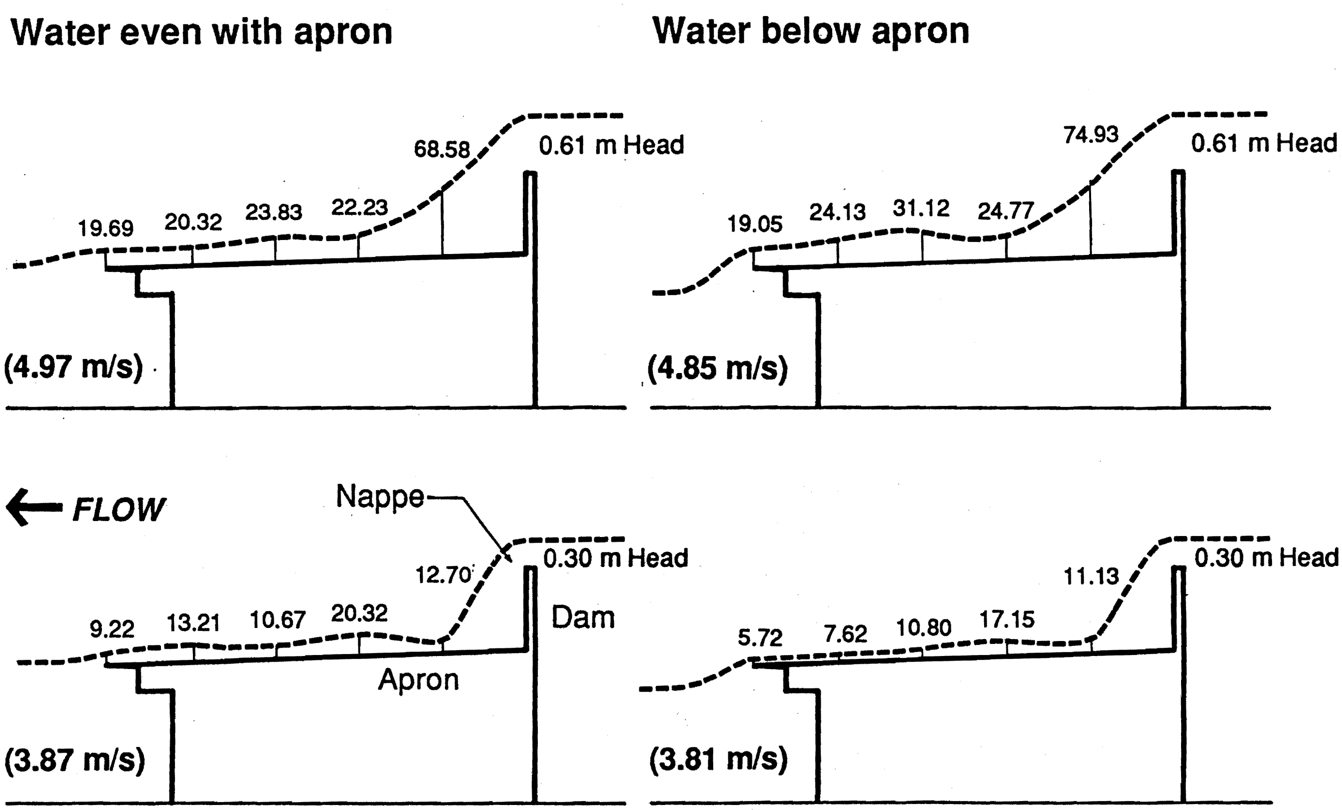


Figure 8.--Side view of the 0.91-m high velocity-barrier dam with a 0.30- and 0.61-m head and the tailwater even with and below the apron illustrating the depth of flow (cm) on the apron, relative position of the nappe as it strikes the apron, and average m/s velocity at the downstream end of the apron.

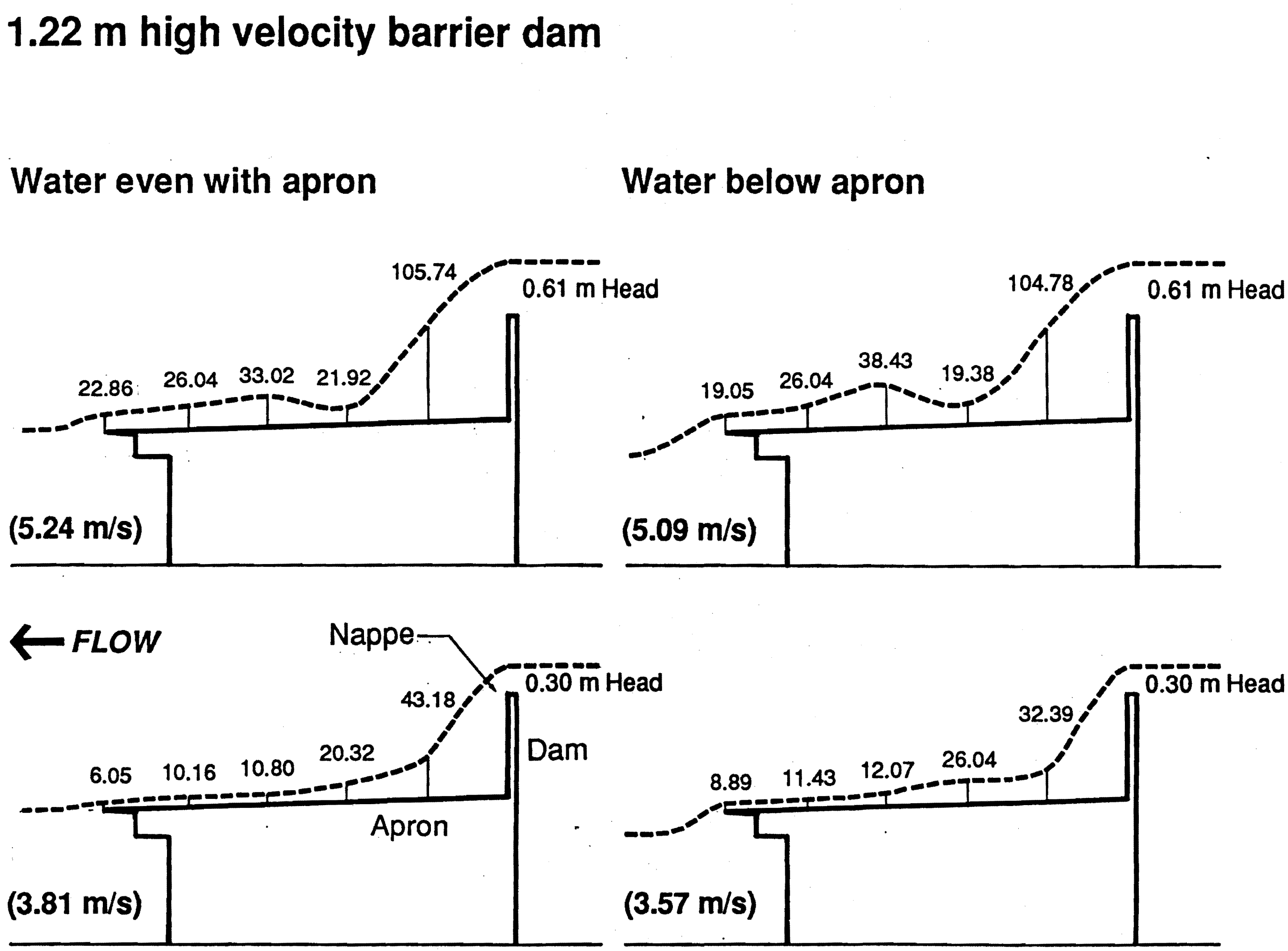


Figure 9.--Side view of the 1.22-m high velocity-barrier dam with a 0.30- and 0.61-m head and the tailwater even with and below the apron illustrating the depth of flow (cm) on the apron, relative position of the nappe as it strikes the apron, and the average m/s velocity at the downstream end of the apron.

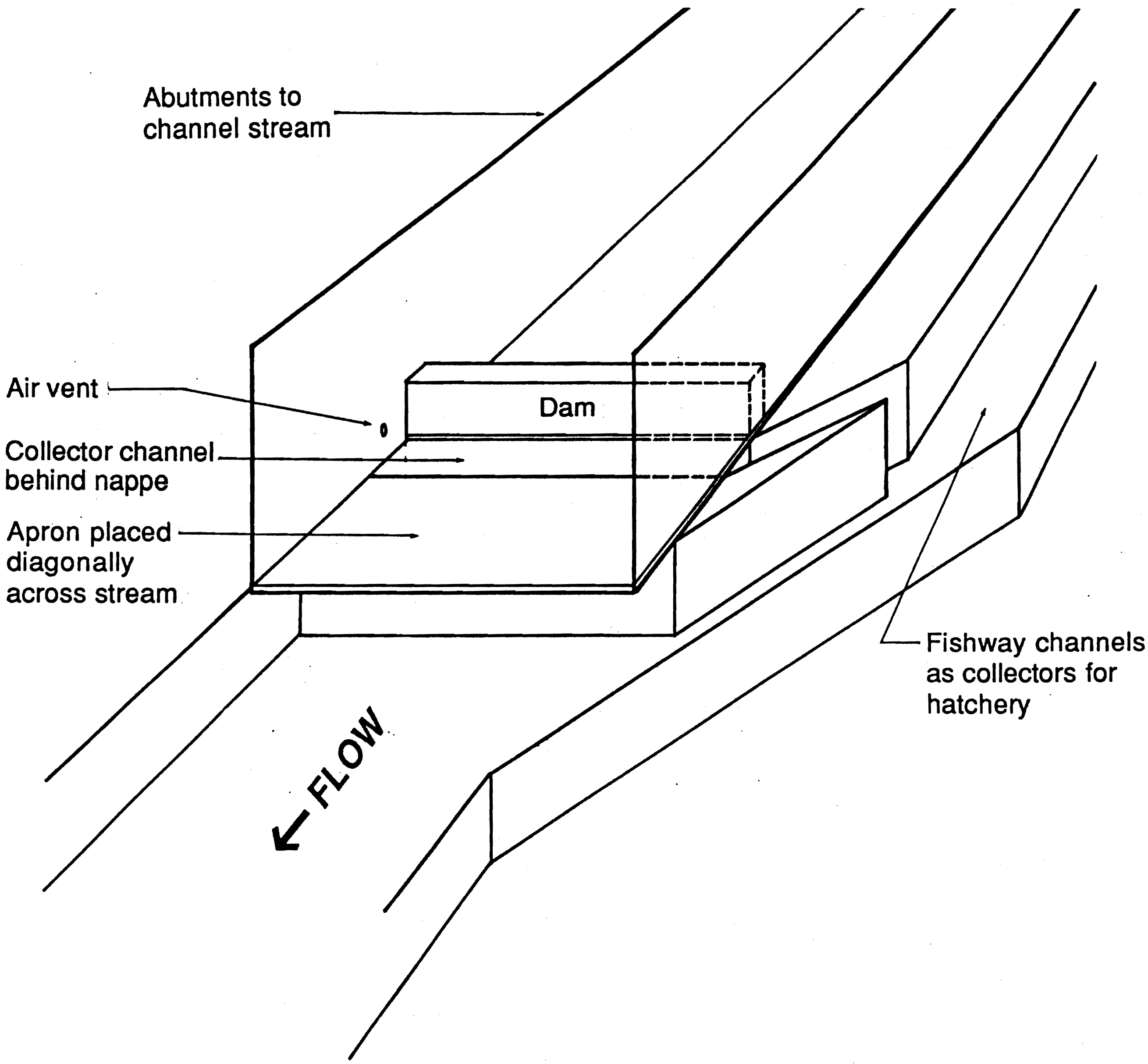
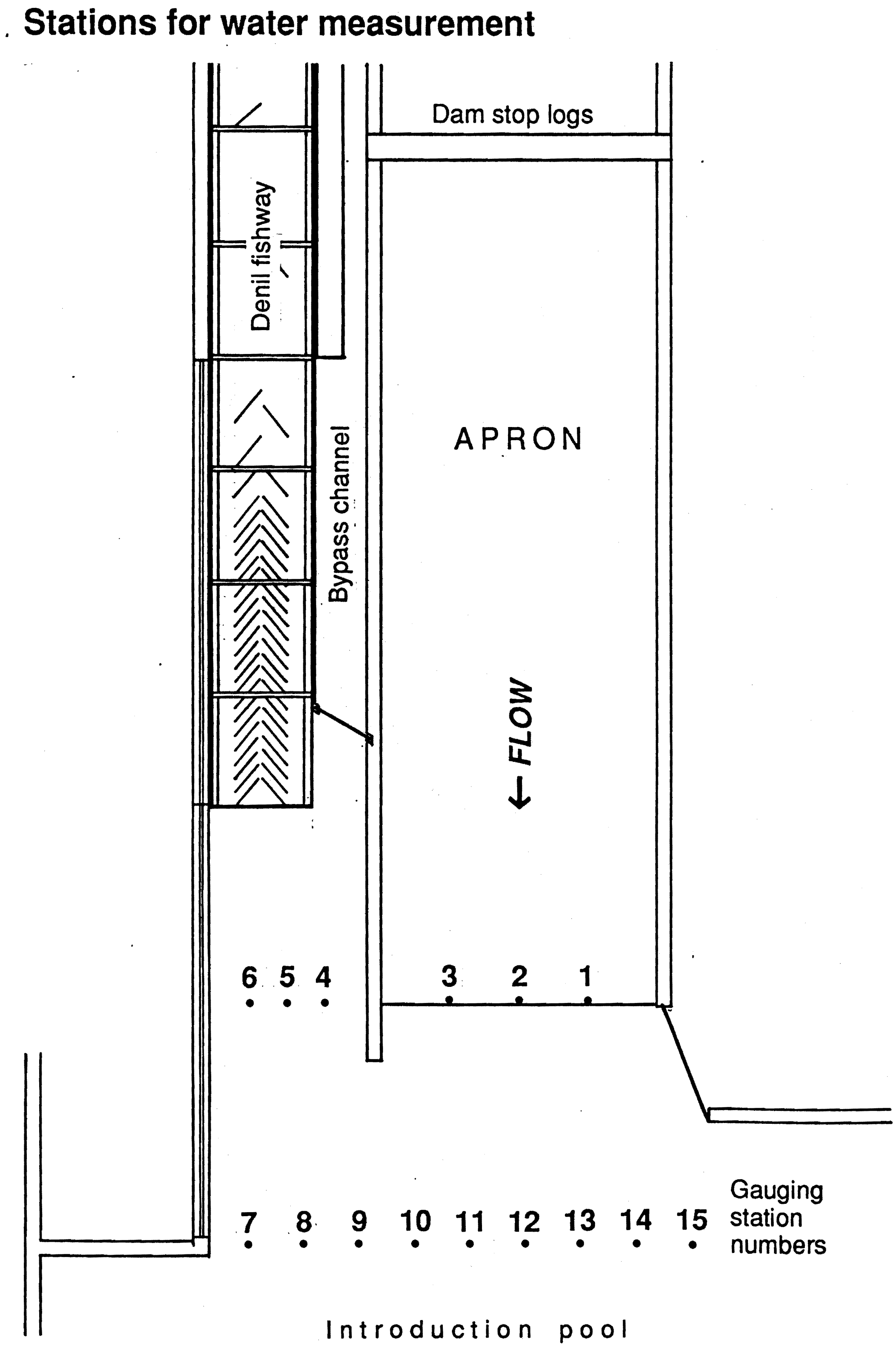


Figure 10.--Isometric view of proposed velocity-barrier dam and locations of fish collection channels.



Appendix Figure 1.--Plan view of velocity-barrier dam and bypass Denil fishway showing gauging station locations used to measure water velocity profiles under various test conditions.