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# Effect of Flow on Performance and Behavior of Chinook Salmon in Fishways

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# Effect of Flow on Performance and Behavior of Chinook Salmon in Fishways

By

CLARK S. THOMPSON

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# CONTENTS

# Effect of Flow on Performance and Behavior of Chinook Salmon in Fishways[1]

by

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## ABSTRACT

Adult fall-run chinook salmon (Oncorhynchus tshawytscha) were studied during plunging and streaming conditions of flow in a pool-and-overfall fishway that permitted recycling of fish after each completed circuit. Flows were controlled by adjustment of valves in a lock at the head of the fishway. Individual fish were timed as they ascended a specified number of pools under each condition.

Combined data on the performance of individual fish and comparisons of combined data from all fish tested suggest that plunging and streaming flows may be equally suitable for the passage of chinook salmon in a pool-and-overfall fishway. About 60 percent of the fish ascended slightly faster in the streaming flow, but the average rate of ascent for all fish was slightly higher in a plunging flow.

Orientation of the fish is described in relation to type and velocity of flow. Most fish preferred to rest in the lower downstream quadrant of the pool in a plunging flow; conversely, the lower upstream quadrant was preferred in a streaming flow. Resting fish always faced the current.

## INTRODUCTION

Pool-and-overfall fishways may operate under two types of flow: (1) a plunging flow in which the directional current reaches the bottom of each fishway pool or (2) a streaming flow in which a strong directional current passes along the top of the pools (fig. 1). Present criteria for pool-and-overfall fishways on the Columbia River stipulate that flows be uniform with a 30.5-cm. to a 38.1-cm. depth over the weirs.[2] Clay (1961) stated that with a head (depth) on the weir up to 35.6 cm., Pacific salmon are able to ascend a fishway where stable streaming flow exists but it is better to limit this head to just under 30.5 cm. or the upper limit of stable plunging flow. The U.S. Army Corps of Engineers (1958) made tests at The Dalles Dam to determine if fish preferred a 45.7-cm. or a 30.5-cm. depth over the weirs. More fish passed the counting station at high, or streaming flows, than at low, on plunging flows.

White and Nemenyi (1942) studied pool overfalls of more than 10 weir profiles in a model flume with constant flows. In a number of examples they showed how submerged flow (plunging) is supplanted by surface flow (streaming) through alterations of the fall between pools, thickness of weirs, and design of the weir crest.

Streaming flow developed when box culverts were weired, but the flows were unsatisfactory because of shallow depths (McKinley and Webb, 1956). Even at relatively low discharges the water tended to go into a streaming motion. The authors added that a successful pool-and-weir fishway requires complete dissipation of kinetic energy of the water in each pool. Sufficient water is also required for the fish to jump the barriers.

During a test of fishway capacity, Elling and Raymond (1959) noted how nonuniform fishway flows affected the passage of fish. When unstable flows changed from plunging to streaming, fish delayed their passage for about 5 minutes. After the delay, the migrants apparently became conditioned to the changed flows and continued their ascent.

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[1] Financed by U.S. Army Corps of Engineers as part of a broad program of fishery-engineering research to provide design criteria for fish-passage facilities at Corps projects on the Columbia River.

[2] Bureau of Commercial Fisheries. 1958. Anadromous fish passage at dams in the Pacific Northwest. Bur. Commer. Fish., 811 N.E. Oregon, P.O. Box 4332, Portland, Oreg. 97208, 10 pp. [Processed.]

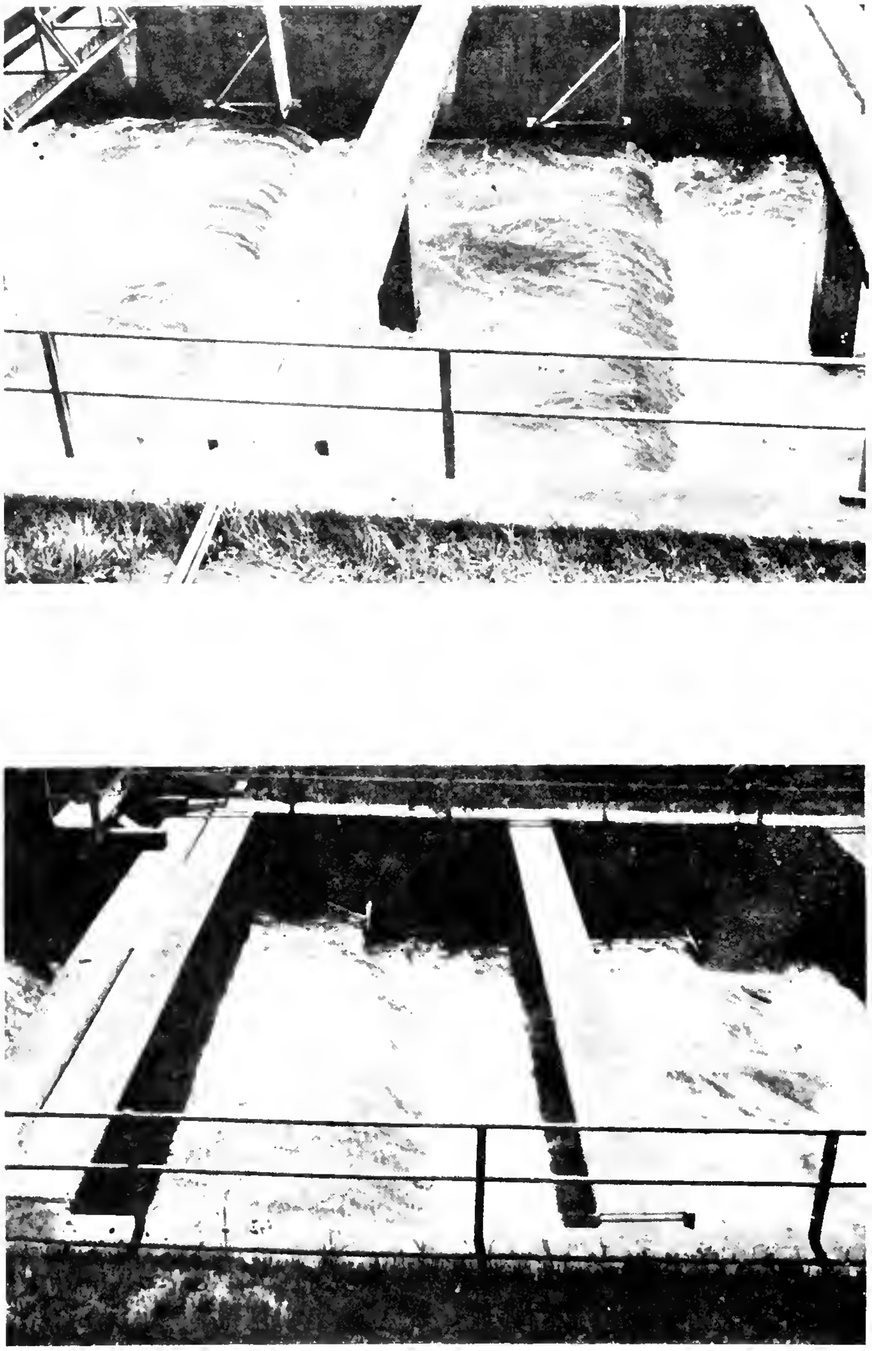

Figure 1.--Plunging (top) and streaming (bottom) flows at the Washington shore fishway, Bonneville Dam. Note that the pool surface in the plunging flow is less turbulent than in the streaming pool.

We studied the performance and behavior of adult chinook salmon in plunging and streaming flows of fishways to determine if one flow was preferable over the other for fish passage. This paper reports on an experiment at The Fisheries-Engineering Research Laboratory, Bonneville Dam, September 12-35, 1959.

## DESCRIPTION OF TEST FISHWAY

An experimental "endless" fishway of pool-and-overfall design with a 1-on-16 slope[3]

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[3] A 1-on-16 slope fishway rises 0.3 m. for every 4.9 m. of length.

was used in this experiment; structural details were given by Collins, Elling, Gauley, and Thompson (1963).

A series of 16 boxlike pools formed the fishway. Figures 2 and 3 show the helical arrangement of the pools and details of construction. All principal structures were of wood, and except for the crests of weirs, all interior surfaces were painted camouflage brown. The surface of each weir crest was painted white to aid in the observation of fish. The weirs had no orifices, but a 5-cm.-diameter hole was provided to permit drainage. Crests of weirs were square and 5 cm. thick.

The connecting link of the 16-pool circuit was the locking pool (pool 1). Fish could be lowered from the uppermost to the lowermost elevation to begin another ascent of the fishway while a diffusion chamber built into the downstream end of the locking pool provided a continuous water supply for the fishway (fig. 2).

Light conditions were constant. Thousand-watt mercury-vapor lights placed 1.8 m. above the water at 1.8-m. intervals throughout the course of the fishway provided an average light intensity of 800 foot-candles at the water surface.

The outer wall of pool 13 was faced with clear plastic 19 mm. thick, to facilitate observation (fig. 3). Other than during turbid conditions (Secchi disc readings below 0.6 m.), most of the pool area was visible under the prevailing light and hydraulic conditions.

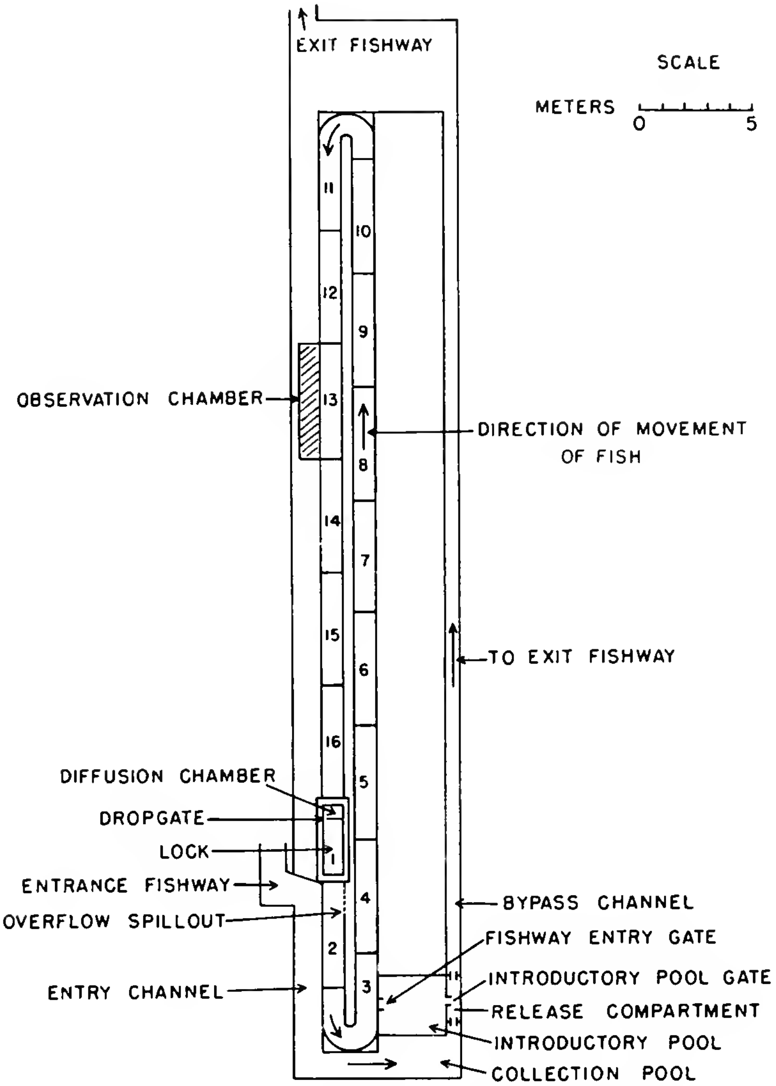

Figure 2.--Plan view of the 1-on-16 slope endless fishway with auxiliary approach channels and pools.

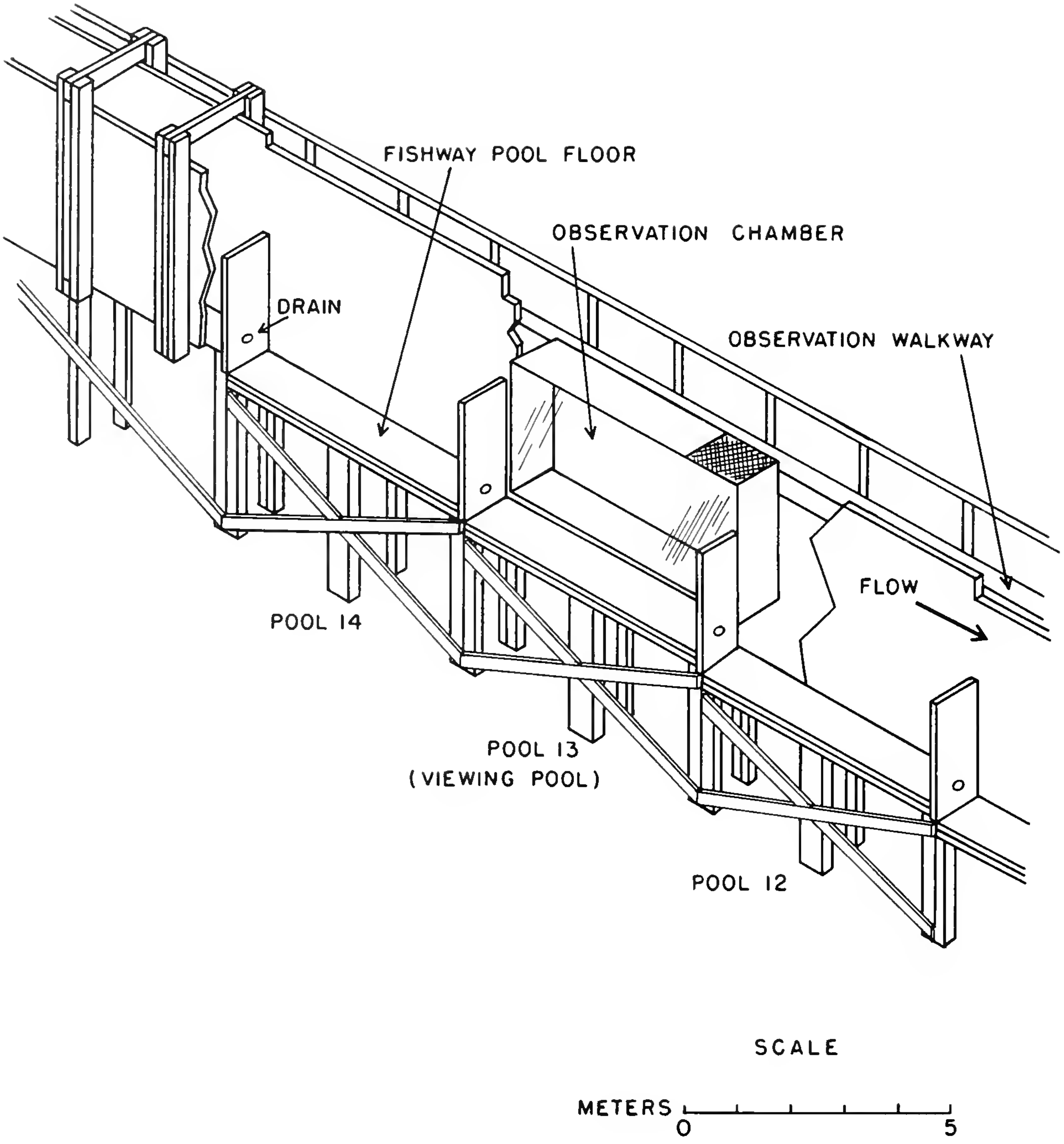

Figure 3.--Section of the 1-on-16 slope endless fishway showing pool construction and location of observation chamber. Each pool was 4.9 m. long, 0.9 m. wide, and 1.8 m. deep. Note level floors in fishway pools.

## TYPES OF FLOW IN FISHWAY

Water for operation of the fishway came from the forebay of Bonneville Dam. Forebay levels at the dam fluctuated between elevations of 22.2 m. and 22.4 m. above mean sea level. The level of the uppermost pool in the experimental fishway was 20.4 m. and provided a minimum operating head of 1.8 m.

Plunging and streaming flows were produced by adjustment of the valves that controlled volume of flow and head on the weirs. The head on the weir was defined as the difference between the elevation of the weir crest and the pool surface measured 0.9 m. upstream from the weir. About 24.4 cm. was the maximum head at which a plunging flow could be maintained. Increasing the head to 30.5 cm. produced streaming flows in all fishway pools. Average water depth in the pools was 2.07 to 2.13 m., depending on the prevailing flow.

## Plunging Flow

In typical plunging flow, the directional flow or jet strikes downward and becomes fully submerged as it sweeps the bottom of the pool (fig. 4). Large air masses form around the plunge of flow at the weir. The trapped air is carried downward and then upward, where it dissipates along the surface in the countercurrent. Relatively few air bubbles pass downstream over the next weir crest.

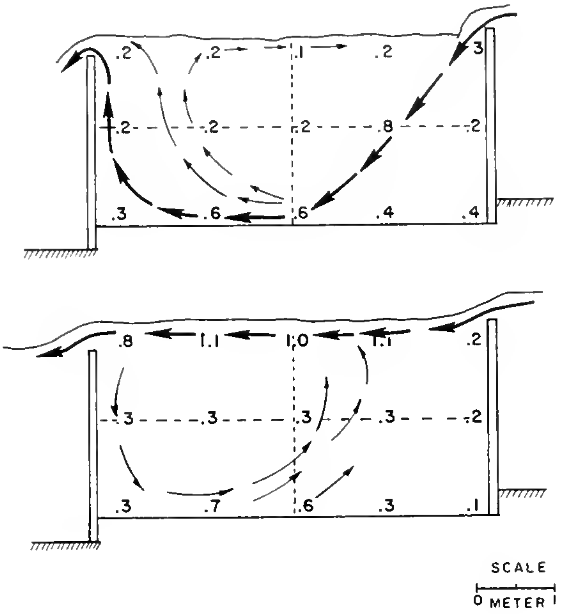

Figure 4.--Plunging (top) and streaming (bottom) flow characteristics depicted in a sectional profile of a typical pool. Heavy arrows show the direction of greatest flow; lighter arrows the lesser counter-currents. Velocities in m.p.s. (meters per second) were taken on a plane parallel to the floor of the pool.

Velocities[4] obtained at surface, middepth, and bottom stations in the pool represented the means of three readings of the current meter at each station. Readings were taken on planes parallel to the fishway floor and therefore may not reflect the true maximum velocities in the line of the flow. The highest recorded velocity--0.8 m.p.s. (meters per second)--was in the downward thrust of the overfall jet at middepth. Undoubtedly velocities were higher at the base of the overfall on a plane parallel to the jet. If head between pools were 30.5 cm., a maximum velocity of 2.4 m.p.s. would be expected in the area immediately below and in line with the overfall. Total discharge during the plunging flow was about 2 c.m.s. (cubic meters per second).

## Streaming Flow

Streaming flow was produced by increasing the flow to about 2.8 c.m.s., or a discharge about 40 percent greater than that which gave the plunging flow. Figure 4 illustrates the streaming flow in the experimental fishway. Note the strong directional flow at the surface and lesser counterflows deflecting downward and upstream along the bottom of the pool. Air masses originating in the overfall jet are only partially deflected toward the bottom of the pool with the counterflow. Many air bubbles pass downstream over the crest of the weir.

Velocity profiles (average of three readings) at each station showed a pronounced flow at the surface that decreased from 1.1 m.p.s. near the head of the pool to 0.8 m.p.s. at the overfall. The weaker but still rather prominent counterflow at the bottom of the pool reached a peak velocity of 0.7 m.p.s.

# EXPERIMENTAL PROCEDURE

Rates of ascent and behavior of the fish were used to compare fish passage under conditions of plunging and streaming flow. Comparisons were based on the performance of individual fish that completed six circuits of the 16-pool fishway. Plunging and streaming flows were tested alternately so that each fish completed three circuits under plunging flow and three under streaming flow. Behavior of fish was observed from the chamber adjoining pool 13.

## Passage of Fish

Fish-passage procedures were identical to those developed and used by Collins et al. (1963). Fish were diverted from the Washington shore fishway into an entrance channel leading to the laboratory collection pool (fig. 2). From the collection pool, individual fish entered a release compartment where they were diverted into an introductory pool adjoining pool 3 of the endless fishway. A gate connecting pool 3 with the introductory pool was raised, and the fish were permitted to swim into the fishway. The gate was then closed, and the test began with the fish now in the closed circuit of the fishway.

Two observers followed the fish during its ascent to obtain a record of time spent in each pool. These observations were made from a walkway that encircled the entire fishway. As the fish moved from pool to pool, an observer pressed a switch button on the hand rail at each weir. This signal was transmitted to a time-event recorder which noted the time of passage on a moving tape. A third observer operated the lock and transferred the chronological record of ascent from the recorder to an operations sheet. Each circuit ended when the fish entered the lock and the next one began upon opening the gate between pool 1 and 2

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[4] A cup-type current meter was used to determine velocities of flow.

after the lock was drained. The time required to drain the lock was not included in the circuit time. Since the fish entered the fishway at pool 3, passage times for pools 1 and 2 were not obtained for the first circuit. Pool times obtained as the fish began the seventh circuit were substituted for these missing values in the first circuit.

### Observations of Fish in Viewing Pool

Each time a fish approached pool 13, two observers descended into the observation chamber adjoining the fishway and recorded its movements with respect to its position in the pool. For standard observations, the pool was arbitrarily divided into four equal quadrants. A record of the elapsed time spent in each quadrant was transmitted to the time-event recorder by switch buttons. A separate button for each quadrant enabled the two observers to plot sequentially the path of movement and time spent in each part of the pool. The respective switch buttons were depressed for the period the fish remained in a particular quadrant. When a fish was not visible, no button was pressed, but the elapsed time (for the unobserved period) was nevertheless maintained by notation of the time between observed movements.

## EFFECTS OF PLUNGING AND STREAMING FLOW

Effects on performance and behavior were evaluated by comparing passages of individual fish in alternating plunging and streaming conditions of flow. Eighteen fish were tested; each fish ascended 48 pools under each condition of flow.

### Effect on Performance

Comparison of performance in plunging and streaming flows was based on (1) mean passage time per pool for all tests combined and (2) passage time per circuit by individual performance.

Passage time per pool.--Mean times per pool (table 1) were first examined to determine if performance differed greatly under the two conditions of flow. The total time for ascent of 16 pools was about 5 minutes longer in streaming flow than in plunging flow. Inspection of passage time by individual pools (fig. 5), however, indicated that this difference was largely the result of performance in pool 2, where flows were changed after the fish completed each circuit. Apparently the change of flows from plunging to streaming detained the fish

TABLE 1.--Mean passage times per pool in plunging and streaming flows; based on combined data from performance tests of 18 chinook salmon ascending a 16-pool, 1-on-16 slope fishway

| Pool | Passage time |  |  |
|---|---|---|---|
|  | Plunging flow | Streaming flow | Difference[1/] |
|  | Minutes | Minutes | Minutes |
| 1 | 0.2 | 0.2 | 0.0 |
| 2 | 2.4 | 5.4 | 3.0 |
| 3 | 0.4 | 0.9 | 0.5 |
| 4 | 3.1 | 2.7 | -0.4 |
| 5 | 1.6 | 1.8 | 0.2 |
| 6 | 1.7 | 1.9 | 0.2 |
| 7 | 1.2 | 2.0 | 0.8 |
| 8 | 1.0 | 1.6 | 0.6 |
| 9 | 1.6 | 1.9 | 0.3 |
| 10 | 1.0 | 1.4 | 0.4 |
| 11 | 1.0 | 1.0 | 0.0 |
| 12 | 4.4 | 4.0 | -0.4 |
| 13 | 1.4 | 1.1 | -0.3 |
| 14 | 1.5 | 1.1 | -0.4 |
| 15 | 1.3 | 1.5 | 0.2 |
| 16 | 3.1 | 3.5 | 0.4 |
| Total (per circuit-- 16 pools) | 26.9 | 32.0 | 5.1 |

[1/] Streaming less plunging.

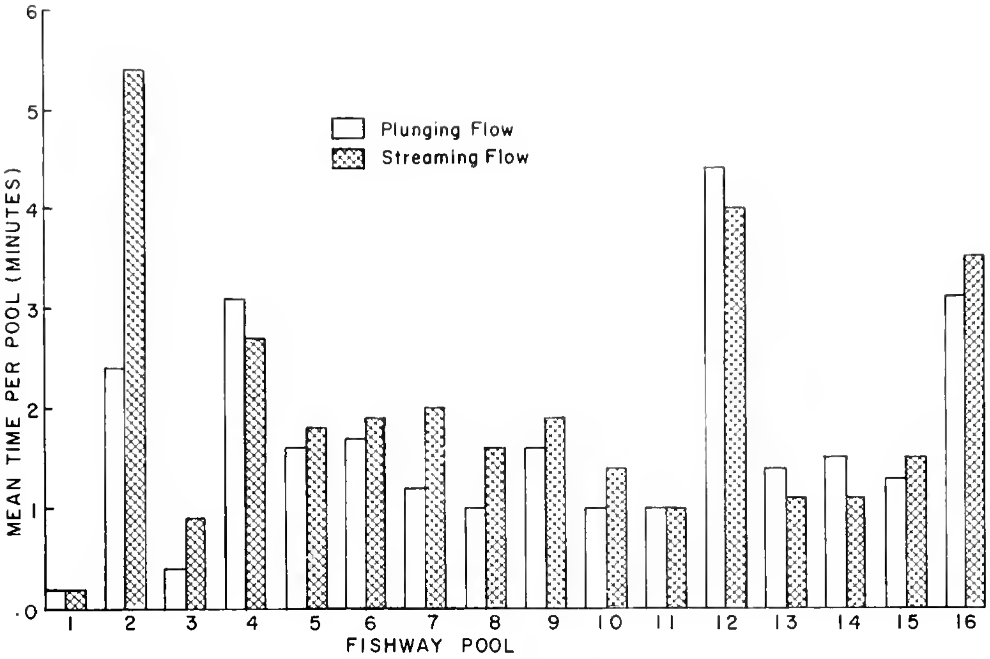


Figure 5.--Comparison of average passage time per pool in plunging and streaming flows (18 chinook salmon, Sept. 12-25, 1959).

longer than did the reverse change from streaming to plunging. In any event, the difference between passage times in pool 2 under the respective flows was clearly apparent and accounted for more than half the difference in total passage time for all pools.

Under the assumption that delays in pool 2 resulted from the changing of flows, we excluded the time spent in this pool to compare passage in established plunging and streaming flows. Mean passage times for ascent of 15 pools under plunging and streaming flows became 24.4 and 26.6 minutes (1.6 and 1.8 minutes per pool).

Passage time per circuit.--Eleven of the 18 test fish ascended slightly faster in the streaming flow, and seven ascended faster in the plunging flow (fig. 6). Of the latter group, five (nos. 6, 7, 13, 15, and 18) ascended

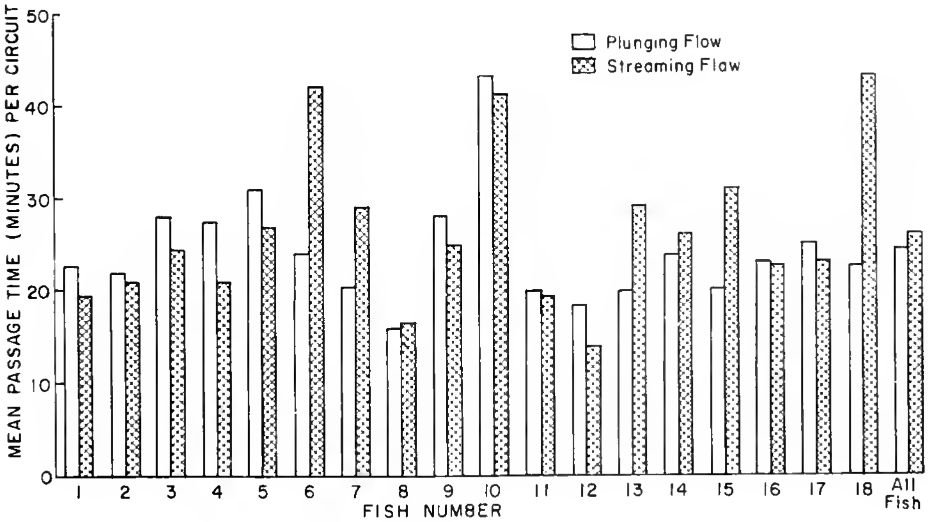


Figure 6.--Mean times per circuit of 18 chinook salmon tested during plunging and streaming flows in the 1-on-16 slope, endless fishway, Sept. 12-25, 1959. Mean time based on three circuits under each flow condition; passage time in pool 2 is omitted.

TABLE 2.--Passage times of 18 chinook salmon that ascended a 1-on-16 slope endless fishway in plunging (circuits 1, 3, and 5) and streaming (circuits 2, 4, and 6) flows (flows were alternated on each successive circuit)

| Passage time per circuit[1] | | | | | | | |
|---|---|---|---|---|---|---|---|
| Plunging flow | | | | Streaming flow | | | |
| Circuits | | | | Circuits | | | |
| 1 | 3 | 5 | Average | 2 | 4 | 6 | Average |
| Minutes | Minutes | Minutes | Minutes | Minutes | Minutes | Minutes | Minutes |
| 26.8 | 22.2 | 19.3 | 22.8 | 25.0 | 16.9 | 16.6 | 19.5 |
| 37.6 | 16.5 | 11.6 | 21.9 | 26.1 | 23.6 | 13.6 | 21.1 |
| 28.4 | 24.1 | 31.2 | 27.9 | 25.2 | 23.0 | 25.6 | 24.6 |
| 41.1 | 23.4 | 17.7 | 27.4 | 24.7 | 16.5 | 22.2 | 21.1 |
| 34.4 | 35.8 | 22.5 | 30.9 | 34.6 | 25.4 | 20.1 | 26.7 |
| 17.1 | 26.8 | 28.8 | 24.2 | 43.0 | 46.2 | 36.4 | 41.9 |
| 12.5 | 28.9 | 20.0 | 20.5 | 30.8 | 27.6 | 28.6 | 29.0 |
| 18.0 | 18.9 | 12.1 | 16.3 | 24.0 | 16.4 | 9.2 | 16.5 |
| 34.4 | 26.2 | 23.4 | 28.0 | 38.7 | 18.5 | 17.2 | 24.8 |
| 65.8 | 35.0 | 28.6 | 43.1 | 60.1 | 37.2 | 26.8 | 41.4 |
| 15.8 | 23.1 | 21.3 | 20.1 | 23.4 | 17.9 | 17.6 | 19.6 |
| 16.8 | 18.8 | 20.0 | 18.5 | 17.4 | 13.5 | 11.5 | 14.1 |
| 24.0 | 17.6 | 17.8 | 19.8 | 35.0 | 26.7 | 26.5 | 29.4 |
| 27.3 | 22.7 | 21.3 | 23.8 | 27.1 | 27.3 | 23.4 | 25.9 |
| 25.7 | 24.7 | 10.4 | 20.3 | 41.0 | 28.3 | 23.1 | 30.8 |
| 32.6 | 20.3 | 24.0 | 25.6 | 23.8 | 29.9 | 22.4 | 25.4 |
| 21.9 | 24.2 | 28.4 | 24.8 | 28.2 | 18.8 | 22.5 | 23.2 |
| 28.6 | 23.7 | 15.9 | 22.7 | 43.0 | 45.2 | 40.6 | 42.9 |
| Mean per circuit | | | | | | | |
| 28.3 | 24.0 | 20.8 | | 31.7 | 25.5 | 22.4 | |
| Mean all circuits | | | | | | | |
| | 24.4 | | | | 26.6 | | |

[1] Time in pool 2 excluded

markedly faster in the plunging flow. When all data were combined, however, the difference between performance under the two conditons was negligible.

Passage times during plunging and streaming flows usually decreased on each successive circuit in the respective flows (table 2). This tendency for improved performance during repeated ascents was attributed to learning by Collins, Gauley, and Elling (1962).

## Effect on Behavior

The behavior of the salmon was studied in plunging and streaming flows to determine (1) areas of the pool used and (2) orientation to flow.

Areas of pool used.--Time in pool 13 was recorded according to the quadrant in which the fish was observed. Time spent (resting and moving) in each of the quadrants was expressed as a percentage of total time in the pool (fig. 7). All fish spent most of the total time in the lower half of the pool regardless of the condition of flow. During plunging flow, 76 percent of the time was spent in the lower downstream quadrant (quadrant 2), whereas under streaming flow, the greater portion of time (57 percent) was spent in the lower upstream quadrant (quadrant 3). The average time that fish remained in the viewing pool during each observation was slightly more than 1 minute under both conditions of flow.

Orientation to flow.--A number of behavioral features were evident in the study, but all were classified into three general groups: (A) direct in-line passage through the pool, (B) circuitous passage involving continuous movement, and

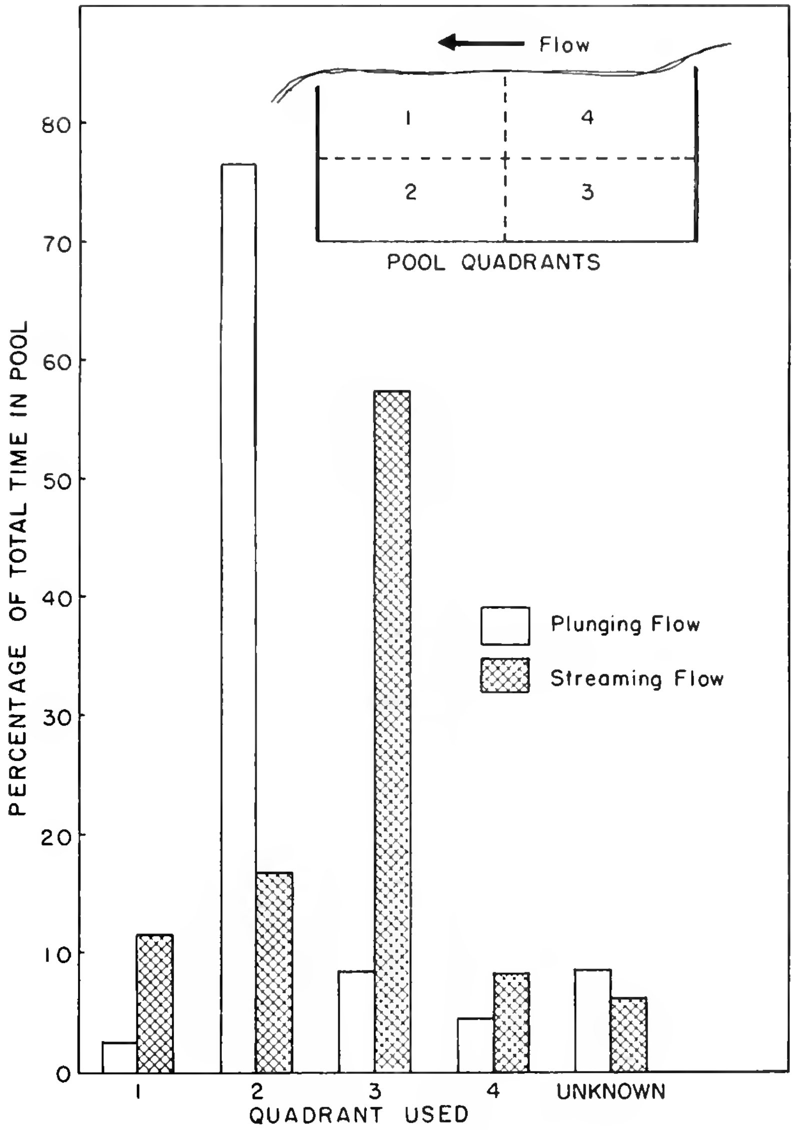


Figure 7.--Pool areas used during plunging and streaming flows.

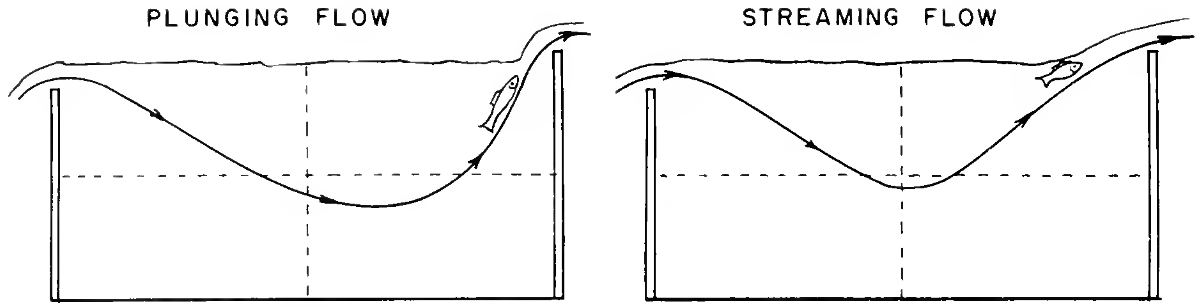
(C) circuitous passage with a rest period. The direct in-line passages were brief, generally about 12 seconds. Circuitous passages that included continuous movement were slightly longer but usually less than 45 seconds. Circuitous passages involving a rest period were nearly always longer, usually more than 1 minute.

The movement of each fish was plotted by transferring the taped observations to a sketched outline. The three basic types of behavior in plunging and streaming flows are illustrated diagrammatically in figure 8. Movements of individual fish differed greatly. Many of the charted movements were too complex for diagrammatic presentation.

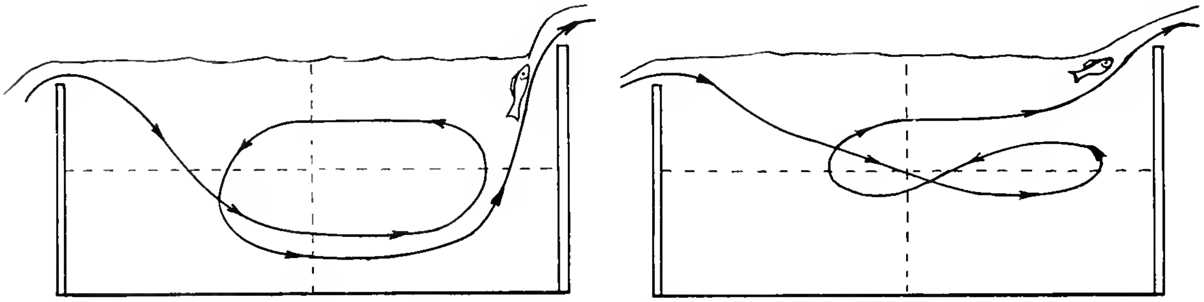
Orientation of fish before exit from the pool usually was in line with the strong directional flow at the base of the weir overfall. During plunging flow, the fish usually aligned themselves either diagonally or almost vertically in the overfall jet at about middepth in the pool (fig. 8). When flows were streaming, the fish approached the surface of the pool and aligned themselves almost parallel to the floor in the strong surface flow. This difference in orientation under the two types of flow was characteristic of all fish regardless of other aspects of the basic behavior (A, B, or C).

Fish were relatively inactive at times under both conditions of flow. Positions of rest, usually near the bottom of the pool, showed that fish faced the prevailing current. Thus, during plunging flow they were aligned toward the upstream end of the pool in quadrant 2, and during streaming flow they faced the downstream end of the pool in quadrant 3 (fig. 8C).

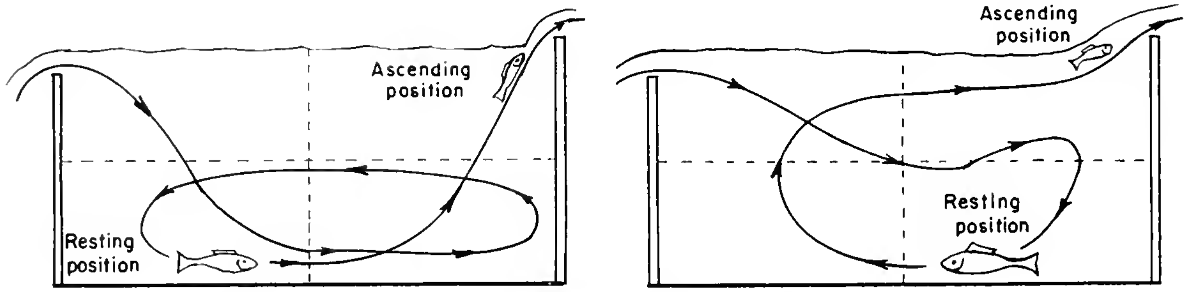
Chinook salmon did not favor a particular type of behavior (i.e., A, B, or C) in either plunging or streaming flow. Observations listed in table 3 were tested by chi-square contingency for frequency of behavior patterns under each condition and between flows. Behavior



A. Direct-in-line passage through the pool.



B. Circuitous passage involving continuous movement.



C. Circuitous passage involving a rest period.

Figure 8.--Types of fish behavior patterns observed during plunging and streaming flow.

TABLE 3.--Types of behavior and mean pool times during plunging and streaming flows

| Type of flow | Type of behavior[1] | Occurrence | | Mean time in pool |
|---|---|---|---|---|
| | | Number | Percent | Minutes |
| Plunging | A | 23 | 39.0 | 0.2 |
| | B | 14 | 24.0 | 0.6 |
| | C | 21 | 36.0 | 3.4 |
| Streaming | A | 21 | 37.5 | 0.2 |
| | B | 16 | 28.6 | 0.7 |
| | C | 19 | 33.9 | 2.9 |

[1] A--Direct in-line passage through pool; B--circuitous passage, continuous movement; and C--circuitous passage rest period. See figure 8.

was independent of flow, and the types of behavior did not differ between plunging and streaming flows (5-percent level).

## SUMMARY AND CONCLUSIONS

Effects of plunging and streaming flow on performance and behavior of fall-run chinook salmon were studied in a 1-on-16 slope experimental endless fishway. Average passage times through the fishway and observations of fish movements within a typical fishway pool were used to evaluate the two flow conditions. In the plunging flow, the directional flow becomes fully submerged and sweeps the bottom of the pool, whereas in streaming flow a strong directional current is produced along the surface of the pool.

The tests indicated that fall-run chinook salmon can ascend a pool-and-overfall fishway without orifices equally well under either plunging or streaming flow. Passage rates through the fishway averaged 1.6 minutes per pool under plunging flow and 1.8 minutes per pool under streaming flow. Eleven of the 18 test fish ascended slightly faster under the streaming flow than under plunging flow and seven made faster ascents under plunging flow.

Observations of fish movements within a typical fishway pool revealed that the behavior of fish under both plunging and streaming flow could be classified into three basic categories: (A) direct in-line passage through the pool, (B) circuitous passage with continuous movement, and (C) circuitous passage with rest period. There was no significant difference in the frequency of the three behavior patterns between plunging and streaming flow. Fish always oriented to the flow while resting and were thus positioned in different quadrants of the pool under the two flow conditions.

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