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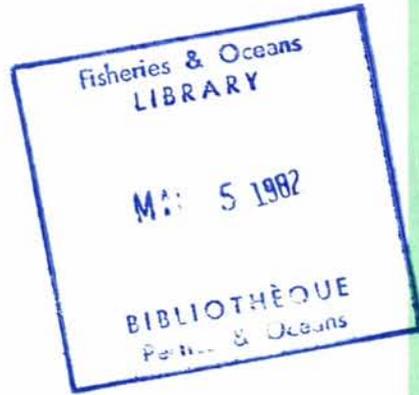


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Evaluation of a Free-Fall Apparatus for Downstream Passage of Atlantic Salmon (*Salmo Salar* L.)

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Freshwater and Anadromous Division
Resource Branch
Department of Fisheries and Oceans
Halifax, Nova Scotia



December, 1981

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Canadian Manuscript Report of Fisheries and Aquatic Sciences

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EVALUATION OF A FREE-FALL APPARATUS
FOR DOWNSTREAM PASSAGE OF
ATLANTIC SALMON (*SALMO SALAR* L.)

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ABSTRACT

Sweeney, R.K. and R.J. Rutherford. 1981. Evaluation of a free-fall apparatus for downstream passage of Atlantic salmon (*Salmo salar* L.). Can. MS Rep. Fish. Aquat. Sci. No. 1632, vii & 7 p.

The design of economical, downstream-passage facilities for Atlantic salmon (*Salmo salar*) kelts and smolts at hydroelectric dams often includes a free fall to the tailrace. To determine the height of fall which could be tolerated by this species without immediate mortality, kelts and smolts were dropped from a plywood flume with a water discharge of 0.42 m³/sec. The smolts were dropped a vertical distance of 18.0 m, while the kelts, both grilse and older salmon, were dropped from both 10.6 m and 18.0 m. Survival was dependent upon impact velocity, with fatal injuries occurring above 15.2 m/sec. The experimental results indicate that this velocity would be reached when smolts fell 21 m, grilse kelts 18 m and salmon kelts 16 m.

Key words: Downstream fish passage, Atlantic salmon, kelts, smolt, free-fall apparatus, bypass facilities, lethal impact velocity.

RÉSUMÉ

Sweeney, R.K. and R.J. Rutherford. 1981. Evaluation of a free-fall apparatus for downstream passage of Atlantic salmon (*Salmo salar* L.). Can. MS Rep. Fish. Aquat. Sci. No. 1632, vii & 7 p.

Les installations économiques pour la migration d'avalaison de smolts et de charognards de saumon atlantique (*Salmo salar*) aux barrages hydro-électriques comportent souvent une chute libre au canal de fuite. Dans le but de déterminer la hauteur de chute que cette espèce peut tolérer sans mortalité instantanée, on a fait tomber des charognards et des smolts d'un canal de bois lamine avec un débit d'eau de 0,42 m³/s. On fit tomber les smolts d'une distance verticale de 18,0 m tandis que pour les charognards, tant grilse que saumons plus âgés, la chute fut de 10,6 et 18,0 m. La survie dépendi de la vitesse d'impact et, à plus de 15,2 m/s, les blessures furent fatales. Les résultats expérimentaux indiquèrent que cette vitesse est atteinte quand les smolts tombent d'une hauteur de 21 m, les grilse charognards de 18 m et les charognards plus âgés de 16 m.

Mots-clés: passes d'avalaison, saumon atlantique, charognards, smolts, appareil de chute libre, installations de dérivation, vitesse d'impact létale.

INTRODUCTION

It has long been recognized, in the provision of fish passage for Atlantic salmon (*Salmo salar*) at dams, that consideration must be given to how the kelts and smolts will pass downstream. In most fish passes, upstream exits are ineffective in collecting downstream migrants. As a result, the fish descend over spillways, or pass through control gates, or power-dam turbines which subject them to various degrees of mortality (Bell et al. 1967; Bell and DeLacy 1972).

Several structures, including louvers (Ruggles and Ryan 1964; Ducharme 1972), guidance screens (Semple and McLeod 1976) and flumes (Semple 1979), have been used at low-head dams to increase survival of downstream Atlantic salmon migrants. However, some of these facilities may involve a free-fall drop of fish into the tailrace; and, although observations have not indicated that mortalities normally occur as a result of these drops, the heights that can be safely tolerated are unknown.

Drops of juvenile Pacific salmon from various heights have been successful in terms of immediate survival. Silver salmon (*Oncorhynchus kisutch*) fingerlings were dropped from approximately 56 m, through the air, with 100% survival of those entering the recapture net (Smith 1938). Schoeneman (1959) passed juvenile silver salmon down a flume 123 m long, of which 106 m was inclined at 22.5 degrees, for a vertical drop of 34.7 m, followed by 7.9-m free fall. Survival rates varied from 95% to 100%, depending on the flume position and the volume of flow. Other similar studies conducted by Schoeneman et al. (1961), Schoeneman and Junge Jr. (1954) and Regenthal (1957) have also shown high survival rates for downstream-migrant juvenile chinook (*Oncorhynchus tshawytscha*) and silver salmon.

Related studies have been conducted by dropping fish from aircraft. Regenthal (1956) found that, in general, the free fall of Pacific salmon species up to 17.5 cm in length from heights up to 91.4 m resulted in negligible mortalities and that fish over 25 cm suffered 'significant' losses from heights greater than 45.7 m, over an observation period of four days. Stocking of two Ontario lakes with yearling and fingerling brook trout (*Salvelinus fontinalis*) dropped 91 m-120 m from aircraft resulted in very low long-term survival rates (Fraser 1968). Their recovery rates after three months were 21%-58% lower for yearlings and 28%-100% lower for fingerlings than for the hand-planted control fish. There were no immediate observed mortalities in the test fish; this suggests that sublethal injuries suffered in the drop may significantly affect the long-term survival in the wild. In a similar study (Anon. 1972), 109,016 Atlantic salmon smolts reared at the Yarmouth Hatchery in Nova Scotia were transported by aircraft and dropped into

the Saint John River, New Brunswick, opposite Mactaquac Hatchery. Control fish were flown to Fredericton and were released in a conventional manner at the same site. "No immediate physiological stress or physical damage resulted from this drop", but returns of the control fish in the following years were seven times higher than those of the test fish (Anon. 1973), indicating a severe loss of air-dropped smolts.

The present study was designed to evaluate the free-fall principle as it relates to the downstream passage of Atlantic salmon kelts and smolts at dams in the Maritime Provinces.

SITE DESCRIPTION

The test site was on the Mersey River, 20 km northwest of Liverpool, Nova Scotia, adjacent to the Mersey Hatchery (Fig. 1).

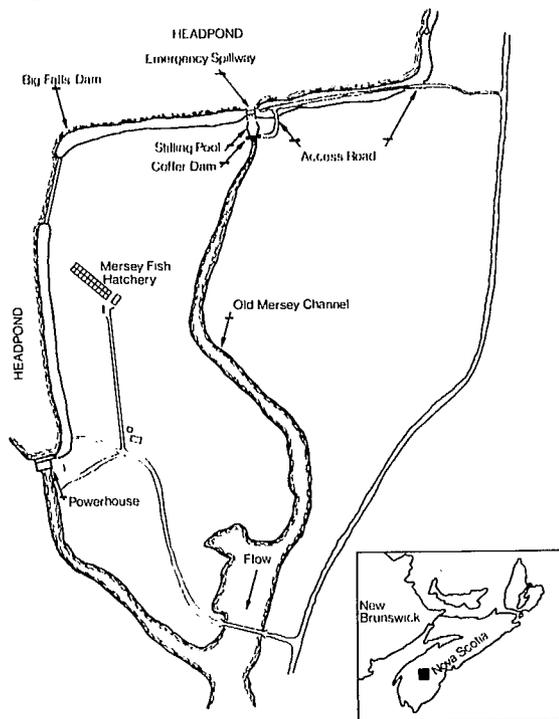


FIG. 1. Location plan, Mersey Hatchery, Nova Scotia.

At this location, the emergency spillway of the Nova Scotia Power Commission's Big Falls Dam provided a 10.3-m drop into a natural stilling pool. The level of this pool was raised by means of an earth cofferdam, to provide a water depth of 2.1 ± 0.3 m in the drop area. During the test, no water was spilled but a slight flow was maintained in the pool by leakage from the stoplog sections.

TEST FACILITIES

The study was conducted in two parts. The first part was conducted on December 5, 1978, when Atlantic salmon kelts were dropped 10.6 m.

In this test, a double section of "A-5", tubular-steel, construction scaffolding was placed on top of the dam to support a plywood diffusion box (1.8 m wide x 2.4 m long x 0.9 m high) set on five 10-cm x 15-cm timbers (Figs. 2 and 3).

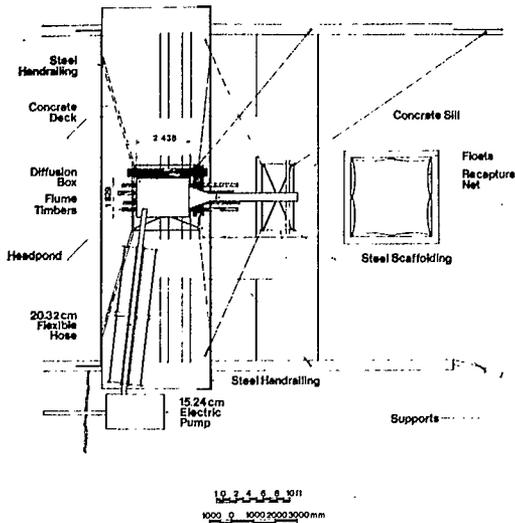


FIG. 2. Free-fall test facilities, plan view.

A 1.2-m-long, funnel-shaped flume section was connected to the 1.0-m-wide x 0.4-m-high exit from the box, to reduce it to the 0.4-m-square flume size. Then 3.7 m of flume was added to extend out over the stilling pool. This was supported on two 5-cm x 20-cm planks at a 5° slope, by nine sections of scaffolding erected on the concrete sill at the base of the central stoplog section.

A 15.2-cm, electric, Monarch pump drew water from the headpond and discharged it into the diffusion box through 9.1 m of 12.5-cm-diameter, rigid discharge hose, supported by timber cribs on scaffold sections. The diffusion box was required to baffle the water discharged from the pump. This provided a relatively smooth flow of 0.42 m³/sec, from the flume, with a velocity of 3.1 m/sec and a depth that averaged 11.5 cm. The water column broke up after a fall of 3.5 m-4.5 m, reaching the pool enclosed by the recapture net as an air-water mixture. The net was a 3.6-m-cube box net of 1.27-cm stretched mesh, as described by Dixon and MacPhail (1977). It was supported on plywood-encased, styrofoam floats, with uprights that held the top edge 0.45 m above the water surface, to prevent fish from escaping. Three polyethylene guide ropes were attached to the floats so that the net could be positioned to best receive the discharge from the flume. It was found in trial runs that the currents created by the discharge caused the net to rise to the surface on the upstream side of the flow and be pulled out of shape in a downstream direction. This was corrected by attaching concrete building blocks to the bottom lead line.

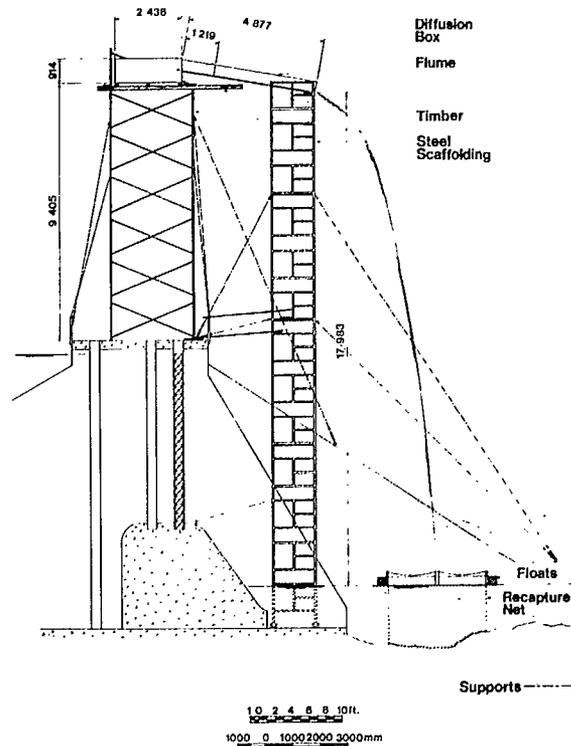


FIG. 3. Free-fall test facilities, elevation view.

The second part of the study was conducted on May 3 and 4, 1979. On these days, both Atlantic salmon kelts and smolts were dropped 18.0 m. The test facilities for these drops were the same as before, except both scaffold towers were raised and supported by guy wires, and the discharge hose was replaced by a more manageable 15.2 m of 20.3-cm-diameter irrigation hose (Fig. 2). Video-tape recordings and "Super-8" movies were made of the fish drops to support observations on the attitude of the fish and duration of the fall. The video recordings were made with a Sony AV 3650 recorder and an AVC 1400 camera with VCL1206 zoom lens. The video equipment was positioned so as to record all the events as they occurred. The "Super-8" camera was hand-held and the operators tried to follow the fish as they fell. Observations were also made on the orientation of the kelts in the flume, as they left it and when they hit the water in the recovery net.

EXPERIMENTAL PROCEDURE

KELT DROP (10.6 m)

Atlantic salmon used in this experiment were captured as they dropped back from Ponhook Lake, Medway River, and were spawned at Mersey Hatchery. Twenty-four of these spawned fish (kelts) were then divided into control and experimental groups, each consisting of 3 male salmon, 3 female salmon, 3 male grilse and 3 female grilse.

The term "grilse" is used to indicate a 1-sea-winter fish, while the term "salmon" includes all 2-sea-winter or older fish.

On December 5, 1978, the fish were transported to the test site by hatchery tank truck. The control fish were placed in containers and ferried out to the recapture net. The experimental group was then trucked to the drop facility, and caudal fins were punched to enable the distinction of experimental fish from control fish. The water supply was turned on, and fish were passed up individually in a dip net and released into the flared section of the flume. After all the fish were dropped, the flow was shut off and the fish were left in the recovery net for 2.5 hours before being transported back to the hatchery. The experimental fish were held for 13 days to permit the determination of delayed mortality and the detection of any behavioural change(s).

KELT AND SMOLT DROP (18.0 m)

The twelve control kelts from the 10.6-m drop and 13 others were overwintered at the hatchery for use in the 18.0-m drop on May 3 and 4, 1979. Post-spawning weight loss during this period was approximately 50% but, otherwise, all the fish appeared healthy. The fish were again divided into control and experimental groups. The controls were made up of 1 male salmon, 5 female salmon, 5 male grilse and 2 female grilse. The experimental group consisted of 2 male salmon, 4 female salmon, 2 male grilse and 6 female grilse. The drop procedure was the same as described above, except each experimental fish was hoisted up to the flume in a burlap bag lined with double plastic garbage bags containing approximately 10 litres of water.

One thousand smolts were also divided into two equal groups, but facilities were not available to mark the experimental fish. The control smolts were therefore placed in the recovery net along with the 13 kelt controls and, following the kelt drops, all fish were removed from the recovery net and returned to the hatchery. The five hundred test smolts were then dropped into an empty net, then taken to the hatchery and held for twelve days. The kelts from this drop were held in a separate pool for 8 days.

The time it took the fish to fall 18.0 m was recorded, and additional data on the time to fall 9.0 m were obtained from the video recordings. By using these times, along with the mean weights of each group of fish dropped, it was possible to estimate the mean impact velocity and to project the mean terminal velocity which would be reached. After leaving the flume, a fish is pulled down by gravity and is slowed in its fall by an upward viscous force proportional to the square of its velocity. These forces are related by the equation $F = mg - KV^2$, where m is the mass, g is the acceleration due to gravity, K is the constant describing the damping force and V is the velocity. The

fish's motion is determined by the differential equation:

$$\frac{d^2x}{dt^2} = g - \frac{K}{m} V^2 \quad (\text{Eisberg 1976}).$$

To solve this equation, time (t) is divided into intervals (Δt) small enough so that the velocity can be assumed to be constant over the interval; in this case Δt was chosen to equal 0.01 sec. Using the modified Euler method (Eisberg 1976), we assume the velocity over the interval is equal to its value at the mid point of the Δt interval. The values for all parameters are known as the fish begins its fall from the flume, and the velocity at the mid point of the first interval can be calculated as

$$V_{\frac{1}{2}} \approx V_0 + a_0 \frac{(\Delta t)}{2},$$

where V_0 is the initial velocity and a_0 is the initial acceleration, and the position by $x_1 \approx x_0 + V_{\frac{1}{2}} \Delta t$; where x_0 is the initial position. This procedure is continued for each Δt . The net downward force is decreased as time goes on by the damping force K , which is unknown; its values must be determined by substitution until the curve generated by the distance/time calculations fits the observed data. The distance/time curve becomes parabolic in shape, assuming a linear behaviour when $KV^2 = mg$. At this point, the fish has reached its terminal velocity, $V_t = \sqrt{\frac{mg}{K}}$.

RESULTS

KELT DROP (10.6 m)

The results of this experiment are summarized (Tables 1 and 2). One of the female grilse escaped while being placed in the flume and was lost in the pool. The remaining fish survived the initial drop and no visible damage or behavioural changes were noted during the 13-day holding period. There was no evidence of shock or confusion while the fish were in the recovery net.

Observations on the orientation of the fish in the flume showed a preference to leave it headfirst. Four of five grilse released tail first turned in the flume to go down headfirst (Table 1). All of the salmon released tail first tried to make the turn but, except for one, were prevented by the physical dimensions of the flume. This tends to confirm observations that an entrained fish trapped in a strong current will rapidly reorient its body so as to pass downward headfirst (Stuart 1962). This reaction has also been observed at Malay Falls flume with salmon smolts (Leeman, pers. comm.)¹.

¹Leeman, J. 1980. Biological technician. Dept. of Fisheries and Oceans, Resource Branch, Freshwater & Anadromous Division, Halifax, Nova Scotia.

TABLE 1. Orientation of falling kelts from a height of 10.6 m.

Group	Sex	Position, entering flume	Position, entering net	Remarks
Grilse	M	Tail first	Headfirst	Turned in flume
Salmon	M	Headfirst	Headfirst	—
Salmon	M	Tail first	Tail first	Tried to turn
Salmon	M	Headfirst	Headfirst	—
Salmon	F	Headfirst	Stomach	Partial turn
Salmon	F	Tail first	Tail first	Tried to turn
Salmon	F	Tail first	Headfirst	Turned in flume
Grilse	F	Tail first	Headfirst	Turned in flume
Grilse	M	Tail first	Headfirst	Turned in flume
Grilse	F	Tail first	Tail first	Tried to turn
Grilse	M	Tail first	Headfirst	Turned in flume

KELT AND SMOLT DROP (18.0 m)

The results of this experiment are also summarized (Table 2). Again, one female salmon escaped during placement in the flume and was lost. The other thirteen survived the initial drop with no apparent ill effects. However, two fish died during the eight-day holding period. A female grilse was discovered dead 40 hours after the drop and a female salmon died after 64 hours. The fish were frozen and sent to the Department's Disease and Nutrition Unit for determination of the cause of death. It was found that both fish died as the result of massive blood clots in the heart area and visible rupture of the aorta (Campbell, pers. comm.)⁴. It was also noted that the grilse had reddened areas near the vent, between the pelvic and pectoral fins, and the salmon had additional hemorrhaging in the left lateral musculature. All the fish in this series of drops were released headfirst in the flume. The orientation of the fish upon impact was found to be 50% headfirst and straight and 50% headfirst but curved, with the tail and lower body taking the impact. The latter group landed very hard and included the grilse that died. The orientation of the salmon was not determined.

Of the 500 smolts dropped from this height, four missed the net and five were recovered dead, with extensive scale loss and severe physical damage that indicated they hit the floats around the recovery net. These fish were not included in survival calculations. There were no immediate mortalities resulting from the drop into the water. Delayed mortalities totaled seven, and all occurred within the first five days. Since almost four times as many control fish died during the holding period, these test-fish

mortalities were not necessarily caused by the fall. It appears that the control smolts may have been adversely affected by their being in the recovery net when the kelts were dropped.

Exact determination of the impact and terminal velocities is impossible because they are dependent on the movement and orientation of the live fish as it falls. This was shown by Richey (1956), who conducted some wind-tunnel experiments on a model of a 12.7-cm sockeye salmon (*Oncorhynchus nerka*) to determine the effect orientation had on the rate of fall. He found that if the model was placed so it simulated a broadside fall, the fish would be expected to have a terminal velocity of 12.2 m/sec. If, however, the model was positioned with its fins retracted and oriented so as to simulate a headfirst drop, the terminal velocity was calculated to be 59.1 m/sec. These proved to be minimum and maximum values for terminal velocities of these fish. Live drops showed a mean terminal velocity to be 15.8 m/sec, just slightly more than the theoretical minimum.

The fish in the present experiment had an initial downward velocity of 0.27 m/sec when they left the flume, because they were entrained in the flow as it moved down the 5° slope. By using the mean mass, mean drop time and a Δt of 0.01 sec for each group - salmon, grilse and smolts - the differential equation for free fall was solved and the resulting curves were plotted (Fig. 4). From these

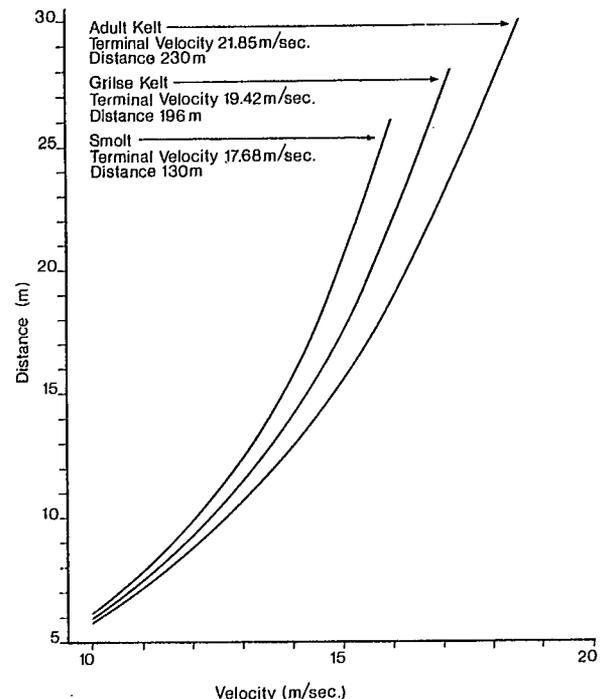


FIG. 4. Velocity vs distance for Atlantic salmon in free fall.

calculations, the expected impact velocity would average 15.8 m/sec for reconditioned

⁴Campbell, M.I. 1979. Biologist, Dept. of Fisheries and Oceans, Resource Branch, Freshwater and Anadromous Division, Halifax, Nova Scotia.

TABLE 2. Summary of results of free-fall experiments with Atlantic salmon.

Tests/Fish groups	No. of fish	\bar{X} length (cm)	\bar{X} weight (kg)	Observ. period (days)	Mortality (no. of fish)			Survival (%)	Drag const. $K(Ns^2m^{-2})$	Terminal velocity VT(m/sec)	Dist. to reach VT (m)	V impact (m/sec)	\bar{X} time to impact (sec)
					Immediate	Delayed	Total						
10.6-m DROP (5 Dec 78)													
<u>Experimental</u>													
Salmon	6	79	4.9	13	0	0	0	100	-	-	-	-	-
Grilse	5	50	1.5	13	0	0	0	100	-	-	-	-	-
<u>Control</u>													
Salmon	6	-	-	150	0	0	0	100	-	-	-	-	-
Grilse	6	-	-	150	0	0	0	100	-	-	-	-	-
18.0-m DROP (3, 4 May 79)													
<u>Experimental</u>													
Salmon	5	79	2.6	8	0	1	1	80.0	0.0547	21.8	230	15.8	2.01
Grilse	8	50	1.0	8	0	1	1	87.5	0.0280	19.4	196	15.1	2.04
Smolt	491	16.5	0.05	12	0	7	7	98.6	0.0018	17.7	130	14.5	1.40
<u>Control</u>													
Salmon	6	-	-	8	0	0	0	100	-	-	-	-	-
Grilse	7	-	-	8	0	0	0	100	-	-	-	-	-
Smolt	500	-	-	12	0	27	27	94.6	-	-	-	-	-

salmon kelts, 15.1 m/sec for reconditioned grilse kelts and 14.5 m/sec for smolts (Table 2). The projected terminal velocities based on these tests would average 21.8 m/sec in a distance of 230 m for salmon, 19.4 m/sec in 196 m for grilse and 17.7 m/sec in 130 m for smolts. These velocities may be in error slightly on the high side since the velocity squared relation to drag is not strictly true at the lower velocities (Richey 1956).

DISCUSSION

When Atlantic salmon were permitted to enter the flume voluntarily, they chose to do so tail first. Once entrained in the flow, they turned to leave the flume headfirst. This was observed in all the experimental fish, although some were prevented from making this turn by the narrow width of the flume. These data show that the flume must have sufficient width to allow the kelts to turn. The orientation of the kelts as they fall depended on how they left the flume. Those leaving headfirst started their fall in a slightly head-down posture, almost at right angles to the vertical direction of fall. This orientation produces the maximum drag. As the fall proceeded, the fish assumed a headfirst orientation and flipped their tails through a wide angle. This orientation permitted the fish to enter the water headfirst, which is its most hydraulically streamlined orientation, and permitted the strain of deceleration to be taken by the fins and tail area, somewhat protecting eyes and internal organs from the shock of impact. Fish leaving the flume tail first either completed the fall by landing tail first or broadside. The velocity on impact was within the same range as for the headfirst fish but the force of impact was more severe.

An attempt was made to determine the lethal velocity. Regenthal (1956) found that serious damage began to occur when the impact velocity exceeded 15.2 m/sec. The mean impact velocities of the salmon and grilse in the present study were 15.8 and 15.1 m/sec, respectively, with one fatal injury sustained from each group. Since no mortalities in the smolt group, with an impact velocity of 14.5 m/sec, could be attributed to the fall, and there were no mortalities in the 10.6-m drop, this study tends to support this 15.2-m/sec velocity as the safe limit.

The size of a fish can be related to the lethal velocity by means of a weight to length ratio (Fig. 5). For fish with a low weight:length ratio, the terminal velocity becomes less than or equal to 15.2 cm/sec and theoretically can be safely dropped from any height. A smolt having a weight:length ratio of ≤ 3.5 g/cm could safely be dropped 21 m, while grilse with a ratio of ≤ 21.5 g/cm could be dropped 18 m and salmon with a ratio of ≤ 33.8 g/cm could be dropped 16 m. These limits give only the assurance that fish

will not sustain immediately fatal injuries upon impact.

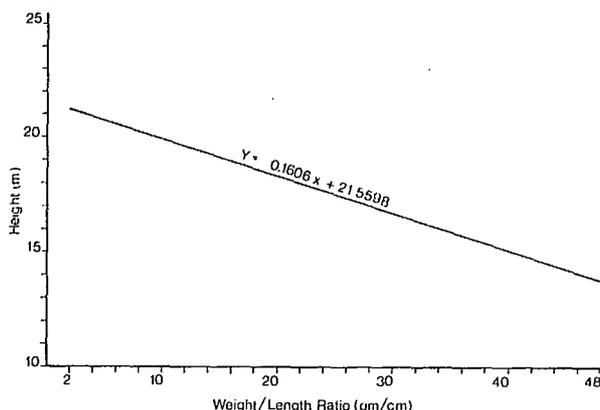


FIG. 5. Height of drop at which a velocity of 15.2 m/sec is attained vs weight:length ratio for Atlantic salmon.

No studies have been found that considered the incidence of other injuries which might be sustained and their long-term effect on survival, but results of drops from aircraft by Fraser (1968) and Anon. (1972) indicate these might be very significant. In neither of the above studies were any immediate mortalities or major injuries observed, yet the long-term survival rate was greatly reduced compared with hand-planted control fish. These observations would indicate that sublethal injuries may occur that make fish unable to compete effectively or cope with stress conditions. Regenthal (1956) examined 60 fish killed in drops of 185-325 feet and found high percentages of gill, kidney, skeletal and liver damage and lesser incidence of eye and heart injuries. Most of the fish had a combination of these injuries, but it is quite reasonable to assume some degree of injury could be sustained without causing short-term death. The height from which fish can be dropped without any debilitating injury has not yet been determined.

If this free-fall method of downstream fish passage is adopted, further studies should be conducted into long-term effect of stress and minor injuries which may be encountered.

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