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Proceedings of the Workshop on Fish Passage at Hydroelectric Developments March 26 - 28, 1991 St. John's, Newfoundland

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PROCEEDINGS OF THE WORKSHOP ON FISH PASSAGE AT HYDROELECTRIC DEVELOPMENTS: MARCH 26-28, 1991, ST. JOHN'S, NEWFOUNDLAND.

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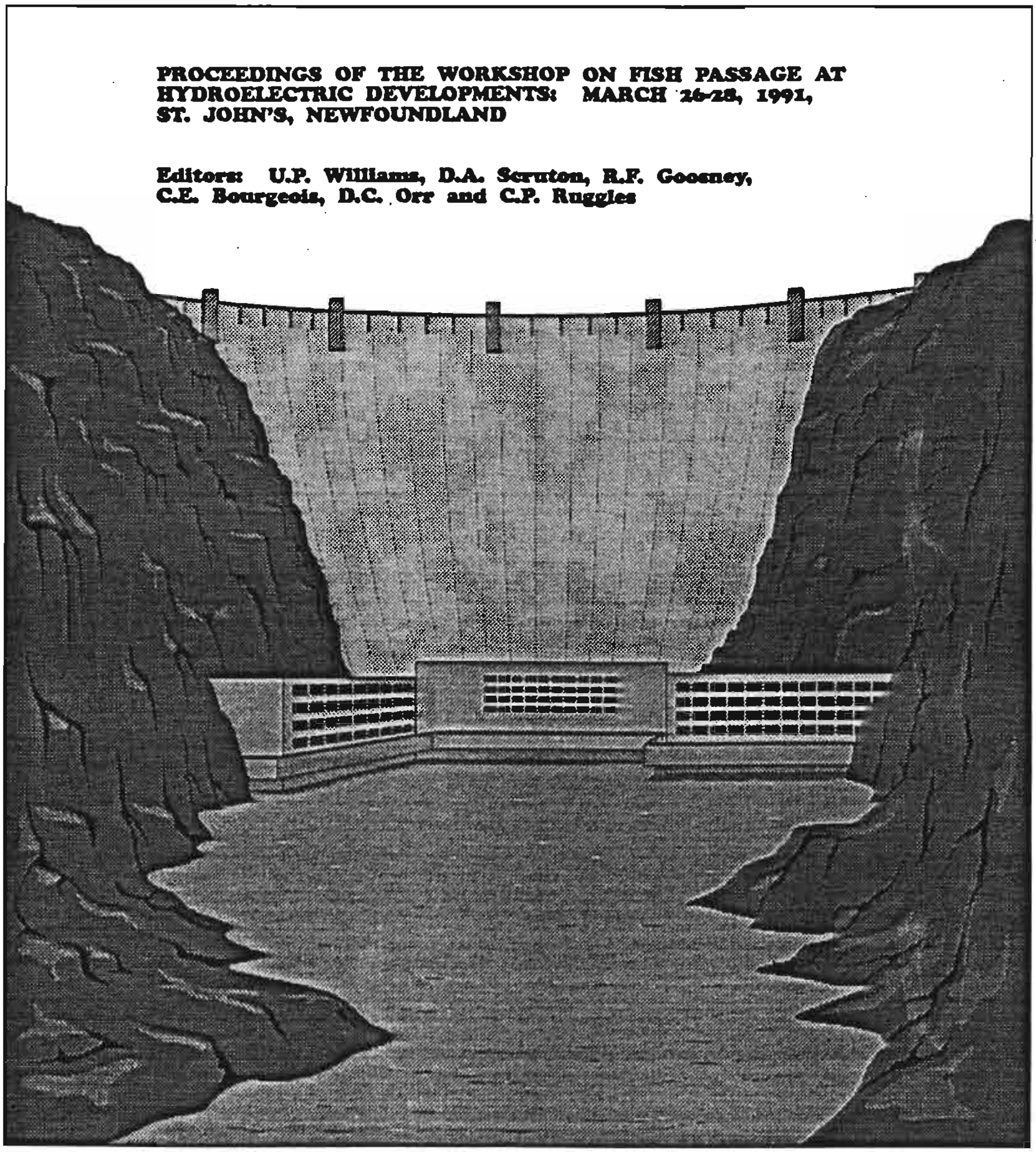

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PREFACE

This publication represents the proceedings of a major workshop on fish passage that was convened to discuss issues related to upstream and downstream fish passage, to ascertain the effectiveness of various options and, if possible, to select preferred options for facilitating fish passage at hydroelectric developments in eastern Canada. The workshop was held in St. John's, Newfoundland, between March 26 and 28, 1991. Recognized authorities in the field of upstream and downstream fish passage from the United States, Canada and the former Soviet Union participated in the workshop and brought a wealth of experience to bear on fish passage problems associated with hydroelectric developments.

The proceedings are being published as a Canadian Technical Report of Fisheries and Aquatic Sciences for broad distribution for those involved in mitigating effects of hydroelectric developments on waterways. The papers contained in these proceedings have been provided by the participants at the workshop. The authors are soley responsible for the scientific content and points of view expressed in the individual papers.

ABSTRACT

Williams, U.P., D.A. Scruton, R.F. Goosney, C.E. Bourgeois, D.C. Orr, and C.P. Ruggles [eds]. 1993. Proceedings of the workshop on fish passage at hydroelectric developments: March 26-28, 1991, St. John's, Newfoundland. Can. Tech. Rep. Fish. Aquat. Sci. No. 1905: *v* + 153 p.

Problems associated with fish passage (upstream and downstream) at hydroelectric developments are well known. Research has been ongoing for years but has failed to identify mitigation that is 100% effective. Due to the controversial nature of this subject, the Science Branch of the Department of Fisheries and Oceans (Newfoundland Region) convened a 3 day workshop to examine the available and emerging technology in fish passage at hydroelectric sites. In an effort to properly address the problem, the workshop covered a variety of relevant topics including turbine technology, sampling methodologies, salmonid biology, as well as passage technology.

The consensus of the participants was that hydroelectric developments and fish do not mix. The complex mixture of biotic and abiotic factors that must be taken into account in designing mitigations has precluded the general acceptance of any one method and highlights the need to evaluate mitigations on a case-by-case basis. Proponents of hydroelectric projects should be made aware of the various forms of mitigation early in the planning stages of the hydroelectric project development.

RÉSUMÉ

Williams, U.P., D.A. Scruton, R.F. Goosney, C.E. Bourgeois, D.C. Orr, and C.P. Ruggles [eds]. 1993. Proceedings of the workshop on fish passage at hydroelectric developments: March 26-28, 1991, St. John's, Newfoundland. Can. Tech. Rep. Fish. Aquat. Sci. No. 1905: *v* + 153 p.

Les problèmes associés au passage des poissons (vers l'amont et l'aval) aux aménagements hydro-électriques sont bien connus. Les recherches menées depuis des années ne sont pas parvenues à arrêter de mesure de correction efficace à 100 p. cent. Vu la nature controversée de la question, la Direction des sciences du ministère des Pêches et des Océans, région de Terre-Neuve, a organisé un atelier de trois jours pour étudier les techniques actuelles et naissantes susceptibles de faciliter le passage des poissons aux aménagements hydro-électriques. Afin d'évaluer le problème dans son ensemble, l'atelier s'est penché sur la technologie des turbines, les méthods d'échantillonnage, la biologie des salmonidés et les techniques de passes migratoires.

Les participants se sont entendus sur le fait que les ouvrages hydro-électriques sont construits au détriment de l'environnement des poissons. L'ensemble complexe de facteurs biotiques et non biotiques dont il faut tenir compte au moment d'élaborer des mesures de correction exclut le recours généralisé à une seule méthode et met en évidence le besoin d'évaluer ces mesures cas par cas. Les promoteur d'ouvrages hydro-électriques doivent être sensibilisés aux diverses mesures de correction dès les premiers stades de la planification des travaux.

HYDROELECTRIC TURBINES PRESENTLY IN USE

HYDRO TURBINES - AN INTRODUCTION

by

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ABSTRACT

This paper describes the various types of hydraulic turbines currently used in hydro powerplants. It is intended for use by non-engineers who are concerned with fish passage and fish mortality at a hydro power facilities. Terminology used in the hydro industry is explained and an equation which measures the extent of cavitation likely to be experienced in a turbine is introduced. Finally, an example of how the cavitation index (gamma) can be calculated is provided for two typical powerplants.

INTRODUCTION

Hydraulic turbines (water wheels) have been used to provide power for many centuries. The first engineer who described turbines was Bélidor who completed a four volume work in 1753 on "Architecture Hydraulique". Turbine efficiencies at that time were in the range of 15 to 20%. Now, a quarter of a millennium later, turbine efficiencies are peaking at 93 to 95%, and there are many different types of turbines ranging in size from small compact units which can fit in the trunk of a car, to turbines with diameters of almost 10 m.

Each type of turbine is housed in a different type of powerhouse. The schematic diagrams in Figure 1 show the range of powerhouse shapes likely to be encountered.

TERMINOLOGY

In order to understand how a turbine works some technical terms have to be used. These are defined as follows:

Kilowatt: Generator output obtained from meters on the control panel in a powerplant. When calculating the turbine cavitation potential it is important to use the power output at the time of fish passage, not the generator rated output.

Head: This is the vertical difference in elevation between the reservoir water level at the intake and the lower water level at the powerhouse outlet. It is usually denoted by the letter "h" and is measured in metres (m). It can also be called the "gross head" which is as defined above, or the "net head" which is the gross head less the friction head lost in the conduit to the turbine. Normally, net head is approximately 95% of gross head (Figure 2).

Runner: This is the name given to the part of the turbine which rotates in the water and converts the water pressure head into mechanical energy (Figure 3).

Wicket gates: These are moveable gates located just upstream of the runner which can be opened and closed to control the flow of water to the runner. A few turbines are built without wicket gates (Figure 3).

Stay vanes: These are vanes which direct the flow of water to the wicket gates. They are fixed, and do not move (Figure 3).

Casing: This is the water containment spiral-shaped pipe built around the periphery of the turbine to direct water to all parts of the runner. Semi-spiral shapes are also used (Figure 4).

Draft tube: This is the conical-shaped pipe between the runner and the powerhouse outlet wherein the high velocity water emerging from the runner is slowed down before being discharged back into the river. The conical pipe may be straight or bent.

Tailrace: The canal which connects the powerhouse to the river.

Submergence: This is the level of the runner relative to tailrace level (positive when below tailwater and negative when above). It is measured as shown in the schematic on Figure 5.

Cavitation: This is the development of vapour bubbles in the water as it passes through the runner and is due to sub-atmospheric pressure. It is a condition to be avoided.

Cavitation erosion: This is the destructive removal of metal from the runner or other metal parts due to impact resulting from collapse of the cavitation bubble on the metal surface.

Gamma: A measure of the cavitation potential of the turbine, and can be used instead of sigma (Monenco 1990).

TYPES OF TURBINES

Hydraulic turbines can be divided into two general classes:

Impulse turbines - where a jet of water impacts upon buckets attached around the periphery of a wheel. In this case the pressure energy in the water is converted to kinetic energy at the pipe nozzle, and then into mechanical energy by rotation of the wheel under force from the water jet. The following are examples of impulse turbines:

Pelton turbines (L.A. Pelton 1829-1908)
Turgo turbines
Cross-flow turbines

Reaction turbines - where the water pressure causes a curved turbine bucket to rotate, converting the water pressure energy directly into mechanical energy. There are several types of reaction turbines, such as:

Francis turbines (J.B. Francis 1815-1892)
Propeller turbines
Kaplan turbines
Bulb turbines
"S" type tube turbines
Pit turbines
Straflow turbines (rim-generator turbines)

Bulb, "S" type, Pit and Straflow turbines are also known as axial flow turbines, since the water enters the runner in an axial direction. All reaction turbines operate in water. Small turbines usually have the runner located 1 or 2 m above the tailwater, while larger turbines always have the runners submerged below the tailwater, sometimes as deep as 10 m. Impulse turbines, on the other hand, operate in air with the runner approximately 2 m above the high tailwater level. Each type of turbine is described in more detail below.

Pelton turbines: These turbines are used where the head is high, usually in excess of about 250 m. An example is found at Cat Arm in Newfoundland (360 m head, 127 MW capacity) (Figure 6). The turbine usually has a horizontal axis where the output is less than 15 MW, and a vertical axis where outputs are higher. There can be from 4 to 6 jets per runner in a vertical axis unit, and 1 or 2 jets per runner, with 1 or 2 runners (1 runner on each side of the generator) in a horizontal axis unit. In a Pelton turbine the water jet is divided at the bucket, which has cups, and is discharged to each side of the bucket.

Turgo turbines: These turbines can be used where the head is between about 150 and 250 m. They are not very common. In this case there are 1 or 2 jets per wheel. The jets are inclined to the wheel with water discharged from the other side (Figure 7).

Cross-flow turbines: These turbines usually have an output of less than 1.5 MW and a head ranging between about 6 and 20 m. They are mainly used to provide power to remote communities (Figure 8).

Francis turbines: These are the most common type of hydraulic turbines. Water enters the turbine through a steel spiral casing, flows through stay vanes past moveable wicket gates, through the turbine runner which may have 11 to 17 blades, and then out through the draft tube. The generating unit usually has a horizontal axis where the runner diameter is less than 1.8 m, or a vertical axis with larger diameter runners. This type of turbine can be used where the head ranges between 30 and 400 m (Figure 9).

Propeller turbines: These are the second most common type of hydraulic turbines, and are used where the head is between 10 and 40 m. Where the head is less than 25 m, the intake leads to a semi-spiral concrete casing. For heads between 25 and 40 m a steel spiral casing is used. Thereafter the water passage is identical to that for a Francis unit the only difference being that the runner is shaped like a ship's propeller, with 4, 5 or 6 blades. The unit axis is always vertical (Figure 10).

Kaplan: This is a variation of the propeller turbine, wherein the pitch of the turbine blades may be modified slightly to improve efficiency as the load changes.

Bulb turbines: This is a recent development of the propeller turbine wherein the axis is horizontal. The stay vanes are at right angles to the axis, similar to spokes on a wheel. The wicket gates become wedge-shaped shutters used to control flow. The runner may have either fixed blades (propeller) or moveable blades (Kaplan). The draft tube is a very efficient horizontal truncated cone. These turbines are used where the head is less than about 15 m, but can be used for heads up to 25 m. The runner has 3 blades, where the head is less than 5 m, 4 blades when the head is between 5 and 15 m, and 5 blades at higher heads. The generator is housed in a "bulb" upstream of the turbine, hence the name. Runner diameter is larger than about 4 m (Figure 11).

Tube or "S" type turbines: This is a variation of the bulb turbine used when the runner diameter is less than 4 m. Due to the small size of the water passage, the generator cannot fit within an upstream bulb. Instead it is located downstream in the open, with the conical-shaped draft tube angled below the generator in an "S"-shaped bend. Head range and number of blades on the runner are similar to those on bulb turbines (Figure 12).

Pit turbines: This is another variation of the bulb turbine. In a bulb turbine, the turbine and generator rotate at the same speed. In a pit turbine, an epicyclic gear is used to increase the generator speed by a factor of approximately 5. This is a more compact generator that is housed in an open pit that is accessible from above (Figure 13).

Straflow turbines: This is another variation of the bulb turbine wherein the generator rotor is attached to the outside of the runner. There are special seals at the runner to prevent water flowing into the generator. There are several small Straflow units in Germany, with runner diameters of 2 to 3 m. The Straflow turbine at Annalopis, Nova Scotia, is the only large unit built to date (Figure 14). Tidal power plants are expected to be equipped with Straflow units.

CAVITATION

Cavitation is the formation of vapour bubbles in a liquid when the pressure falls below the vapour pressure. It does not usually occur in impulse turbines, but does occur to some extent in most reaction turbines. It is a function of the turbine elevation relative to tailwater, the velocity of the water through the runner, and the pressure loading on the runner blade area, which in turn is a function of the number of runner blades.

The severity of cavitation can be measured by the rate of metal removed from runner blades due to collapse of the vapour bubble. It can range from 0 up to more than 100 kg of metal removed from a large runner each year. Current practice in Canada is to install runners which do not suffer from cavitation erosion. This does not mean that there is no cavitation, it is present, but is not severe, and erosion is controlled by use of cavitation erosion resistant metals such as stainless steel, Stellite and Ireca.

At the powerplant, cavitation can be detected by listening to the sound of the water in the draft tube. A crackling sound indicates moderate cavitation. The sound intensity increases to loud bangs similar to gunshots as cavitation becomes more severe.

SIMPLIFIED TURBINE EQUATIONS

The extent of cavitation is one of the factors affecting mortality rates of fish passing through turbines. In an area of cavitation, local pressure approaches 0 psi, thus becoming a nearly perfect vacuum. According to Bell (1991), fish experience a 100% mortality when absolute pressure drops below 3 psi, or about 2.1 m water head, equivalent to a suction head of 8.2 m. On the suction side of the turbine runner blade, there is usually an area which is close to 0 psi pressure. In this area cavitation forms with the extent and severity being a function of several parameters.

To date it has not been possible to develop a measure for cavitation, without using proprietary model test data, which is rarely available. As a result of research work undertaken for the Canadian Electrical Association, an alternative method has been developed, which uses only available data (Monenco 1990). For this paper, some simplifying assumptions are made which do not significantly affect the determination of the cavitation potential. These are:

- Turbine full load efficiency 89%,
- Generator full load efficiency 98%,
- Runner material cast steel (for fish, the runner material is of no consequence),
- Powerplant capacity factor 60%, and
- Water temperature 10°C.

The turbine runner gamma (γ) number is a measure of the severity of cavitation based on the following:-

$\gamma < 6$	Extreme cavitation.
$6 < \gamma < 8$	Severe cavitation.
$8 < \gamma < 10$	Moderate cavitation.
$10 < \gamma < 12$	Mild cavitation.
$12 < \gamma < 14$	Insignificant cavitation.
$14 < \gamma$	No cavitation.

In order to determine the gamma number, the following parameters must be known:

- Generator output in kilowatts,
- Turbine rated head (h) in metres,
- Turbine runner throat diameter (d) in metres,
- Number of runner blades (b),
- Tailwater elevation (E) in metres above sea level, and
- Turbine submergence (S) in metres.

Turbine submergence requires careful measurement. For a horizontal axis unit, it is the vertical distance between tailwater and a point on the runner $0.1\ d^{1.5}$ above the axis. For a vertical axis unit, the distance is measured to the centerline of the runner blades in a propeller or Kaplan unit, and to a point 0.25 d below the spiral casing centerline in a Francis unit. All are positive when below the tailwater and negative when above (Figure 5).

The simplified equations are:

1) $Q = 0.117\ kW\ h^{-1}$

Q = turbine flow in m^3/s

2) $V = 1.27\ Q\ d^{-2}$

V = nominal runner throat velocity in m/s.

3) $\gamma = 20 - 0.45\ V^2\ b^{-0.56} + S^{\ -0.002E0.92}$

From equation 3 it is evident that gamma is a function of the turbine throat velocity, the number of runner blades, the tailwater elevation and submergence. A gamma number less than 10 indicates sub-atmospheric pressures within the runner. Most modern turbines will have gamma numbers between 8 and 10. Gamma numbers less than 6 are rare, but can occur in runners which suffer from extensive cavitation. A gamma number less than 4 is indicative of a mistake in the calculation.

In other words, a gamma number (γ) below 6 indicates that a large proportion of the suction side of the runner would be subjected to severe cavitation, where the absolute pressure would be near 0 psi, and fish kill would be 100%. On the other hand, a gamma number (γ) of 13 would indicate that a very small and insignificant area of the runner blade was being subjected to cavitation, hence the chance of fish survival would be considerably improved.

EXAMPLES OF GAMMA CALCULATION

(a) Annapolis tidal powerplant

Given:

- Capacity 17,400 kW
- Head 5.5 m
- Runner diameter 7.6 m
- Number of blades 4
- Submergence (Shaft) 4.0 m

Calculate Q from equation 1

$Q = 0.117 \times 17{,}400/5.5$

$= 370\ m^3/s$.

Calculate V from equation 2
$V = 1.27 \times 370/7.6^2$
$= 8.14$ m/s.

Calculate S for horizontal units.
$S = 4.0 - 0.1 \times 7.6^{1.5}$
$= 1.90$ (positive)

Tailwater elevation E = 0.0 (tidewater)

Calculate gamma from equation 3
$\gamma = 20-(0.45 \times 8.14^2/4^{0.56}) + 1.9-0$

Hence $\gamma = 8.2$, moderate cavitation.

Re-calculate for output of 14,000 kW:

$Q = 298\ m^3/s$
$V = 6.55$ m/s
$\gamma = 13$, insignificant cavitation.

This Annapolis (Nova Scotia) example demonstrates that the gamma number is very sensitive to the operating load on the unit. At 17.4 MW output cavitation is moderate, but rapidly reduces to insignificant as the load is reduced to 14 MW. Hence, it is essential to calculate the gamma number for the turbine at time of fish passage, since it changes with changing load and tailwater level.

Lequille powerplant

The Lequille powerplant in Nova Scotia has been used in experiments on fish mortality.

Turbine data are:
- generator capacity 11,200 kW
- rated head 118 m
- runner diameter 1.17 m
- number of blades 13
- casing centerline elevation 2.0 m
- tailwater is tidal (ranging from 1.9 m with unit at full low tide output to 4.1 m at high tide)

With these data, gamma can be calculated at 8.8 (low tide) increasing to 11.0 at high tide, indicating moderate to mild cavitation. It is perhaps significant to note that fish mortality decreased from about 58% when tailwater was close to 1.0 m, to about 43% when tailwater was increased to over 3.0 m, all at 50% wicket gate opening (Ruggles *et al.* 1981).

TURBINE OPERATION

Most hydroelectric turbines are operated between 70 and 95% of full rated load. Occasionally, turbines are operated at smaller loads down to around 30% of full load, particularly Kaplan units where efficiency is relatively high at low loads.

The important point here is to find out how the turbine is operated during fish migration. For example, the Annapolis unit has a maximum output of 20 MW, but has only produced this output during a test. Normal output is 14 MW, increasing to 18 MW when the tidal head is greater than normal.

CONCLUSION

Cavitation indices were developed from available turbine parameters. It is hoped that use of this concept will help to explain differences in fish mortality through similar turbines.

NOMENCLATURE

b - Number of runner blades.
d - Turbine runner throat diameter in metres.
E - Tailwater elevation in metres above sea level.
h - Turbine rated head in metres.
kW- Generator output in kilowatts.
Q - Turbine flow in m^3/s.
S - Turbine submergence in metres.
V - Turbine runner throat velocity in m/s.
γ - gamma, a cavitation index.

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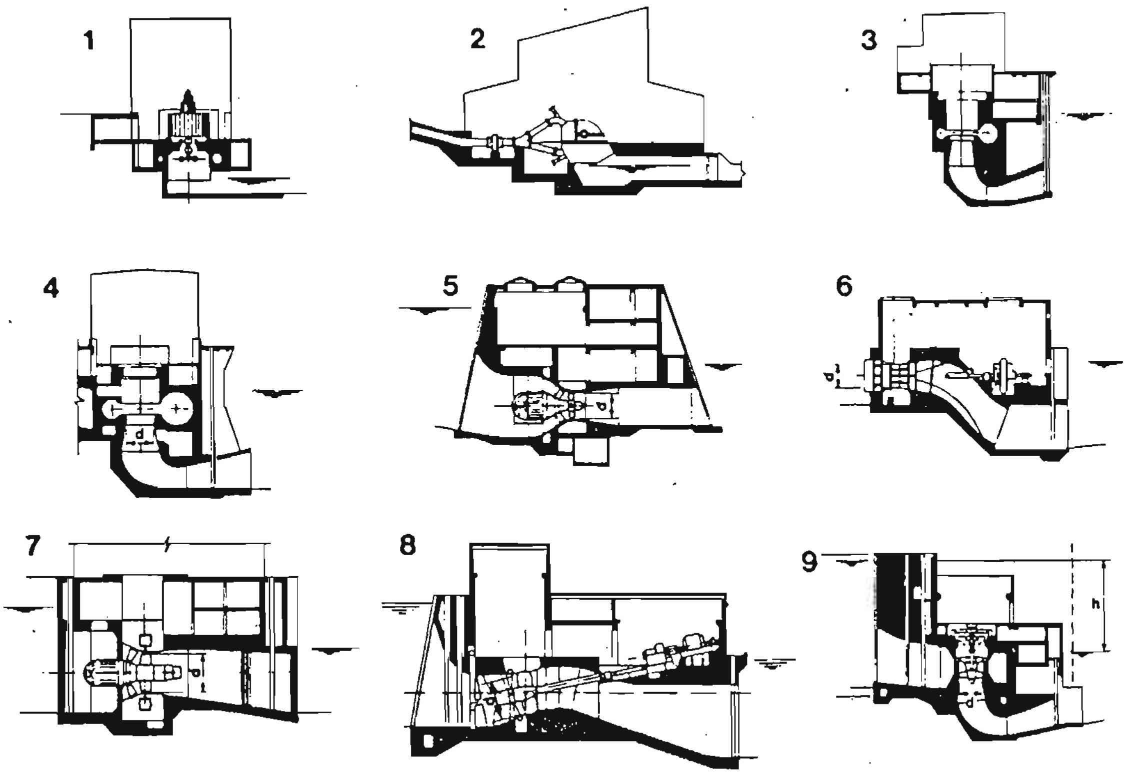


Figure 1. Schematic of powerhouse types.

1. Vertical axis (VA) Pelton turbine,
2. Horizontal axis (HA) Pelton turbine,
3. VA Francis turbine,
4. VA Propeller turbine with spiral casing,
5. HA Bulb turbine,
6. HA Tube with "S" type draft tube,
7. HA Straflow turbine,
8. Tube turbine with inclined axis, and
9. VA Propeller turbine with semi-spiral casing.

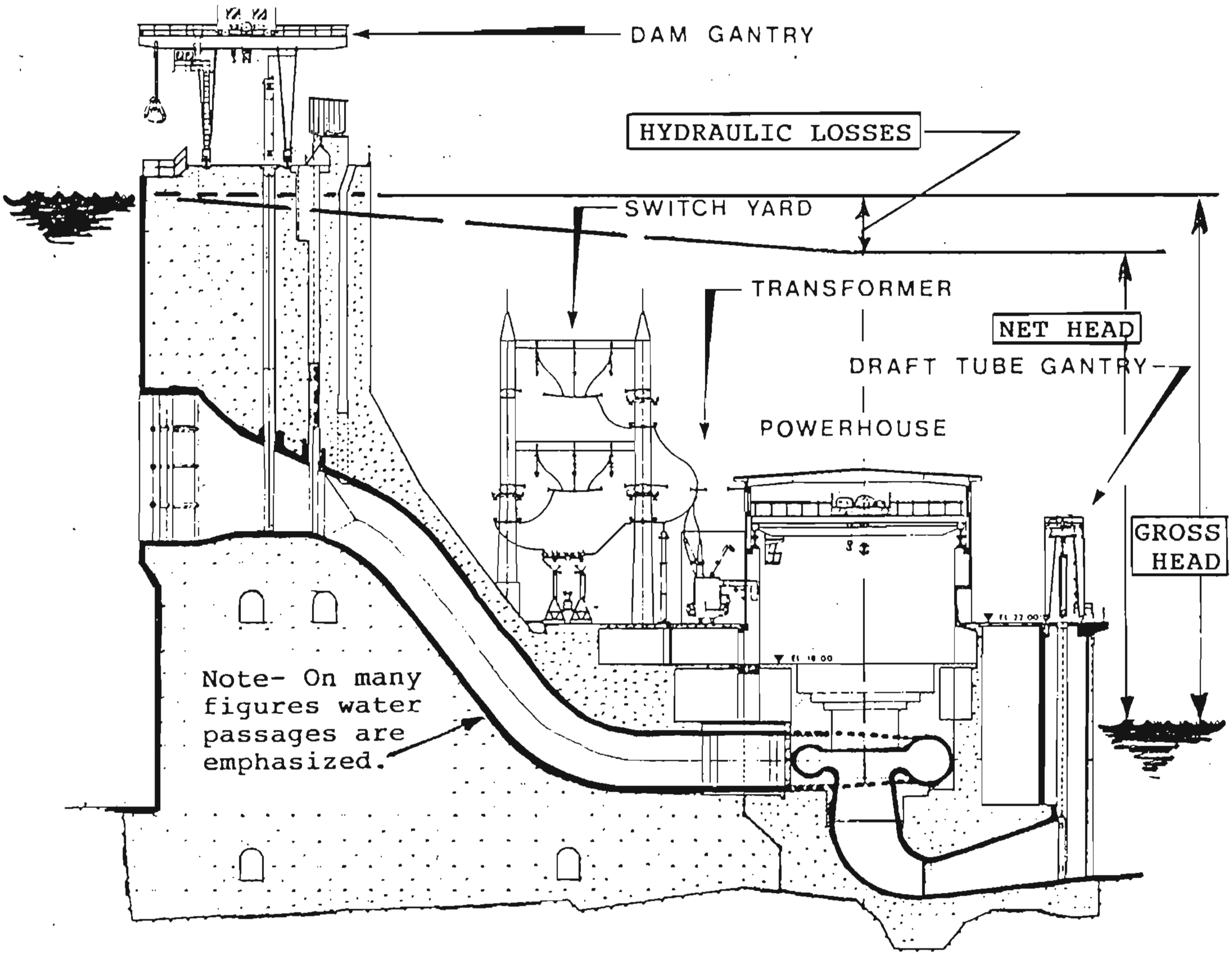


Figure 2. Schematic showing power head.

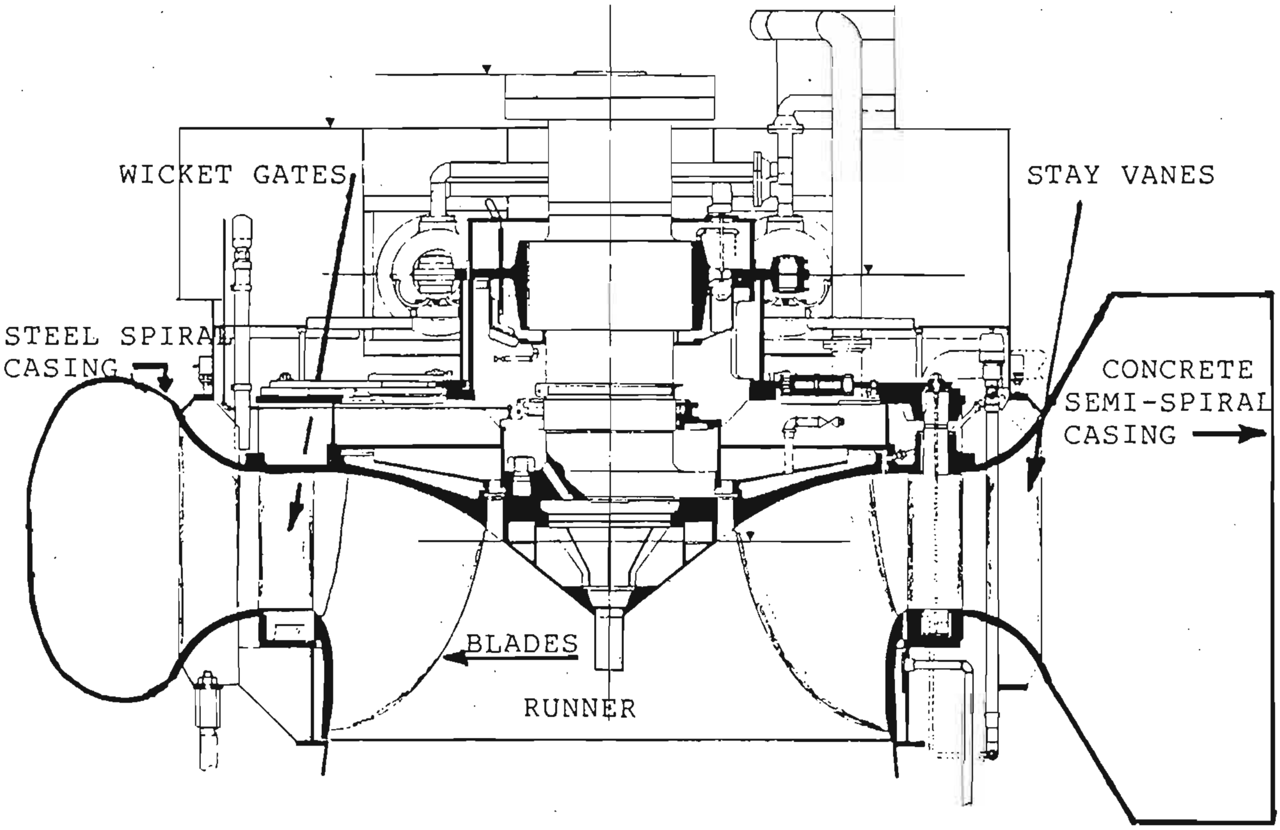


Figure 3. Section through a turbine.

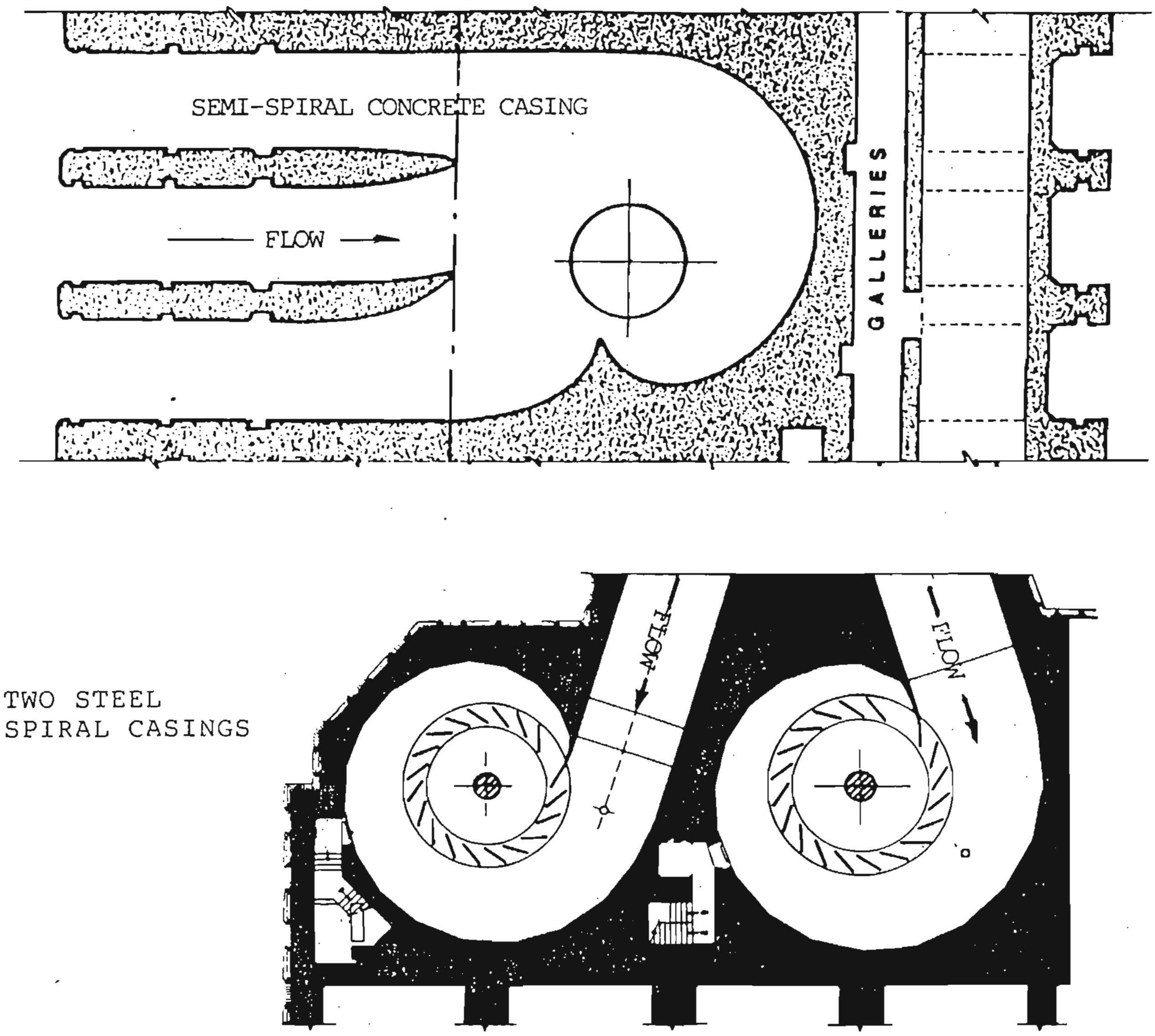


Figure 4. Plans of turbine casings.

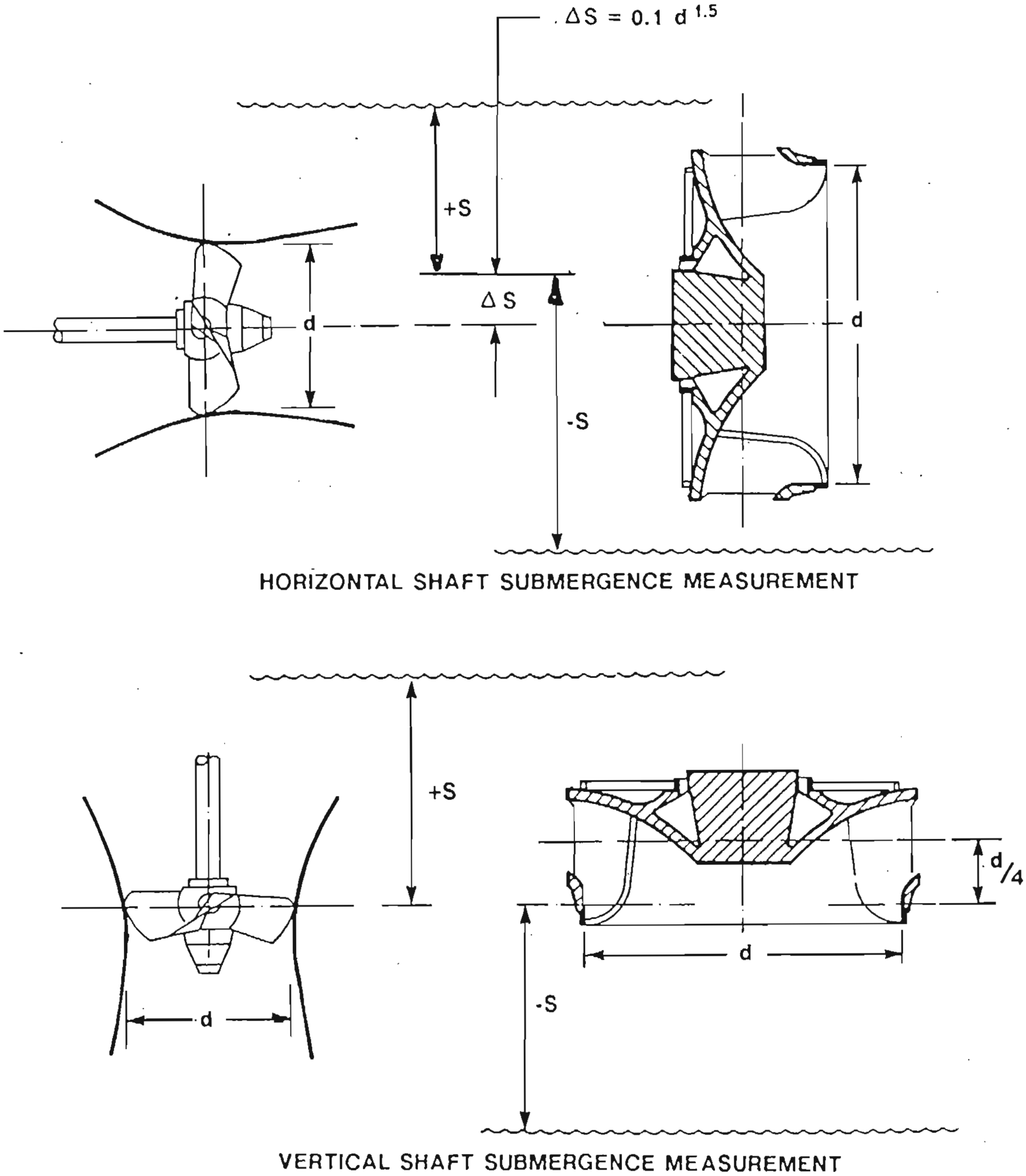


Figure 5. Schematic of submergence measurements.

Legend
s = turbine submergence
d = turbine runner throat diameter

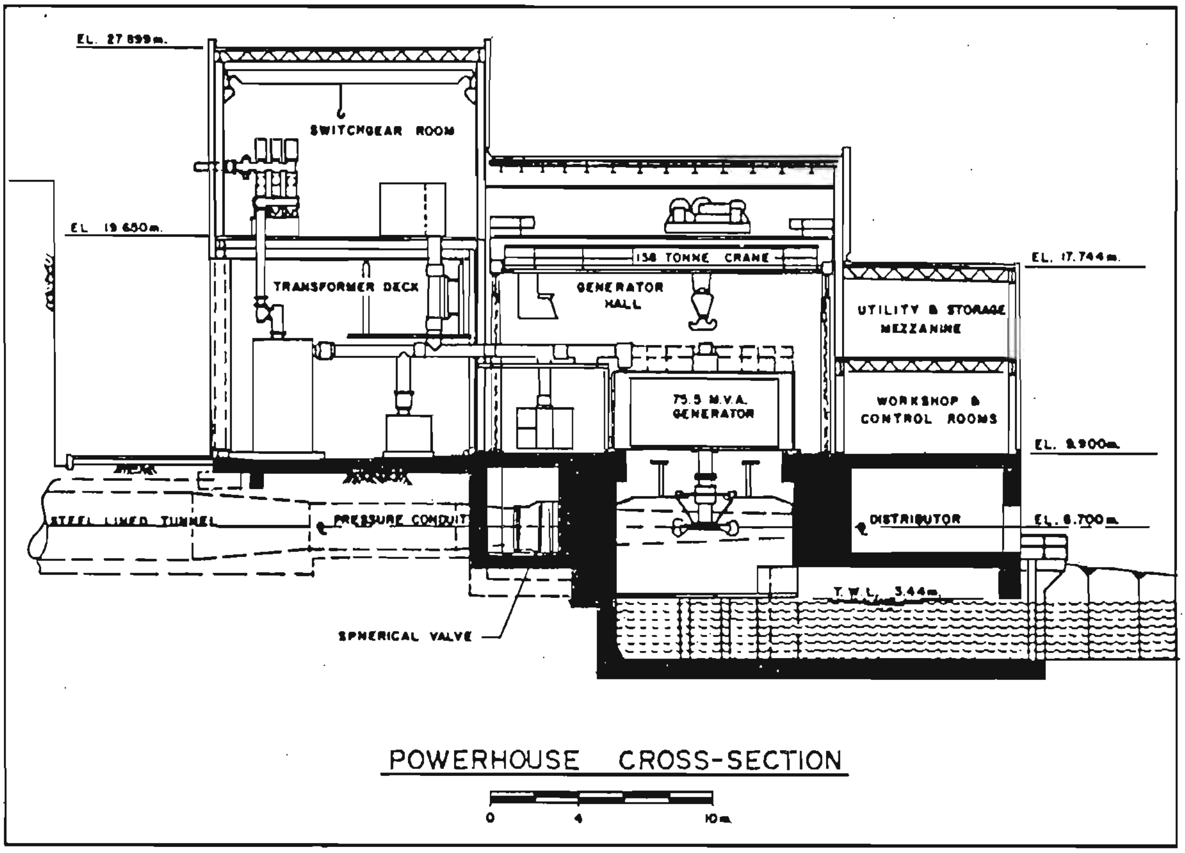
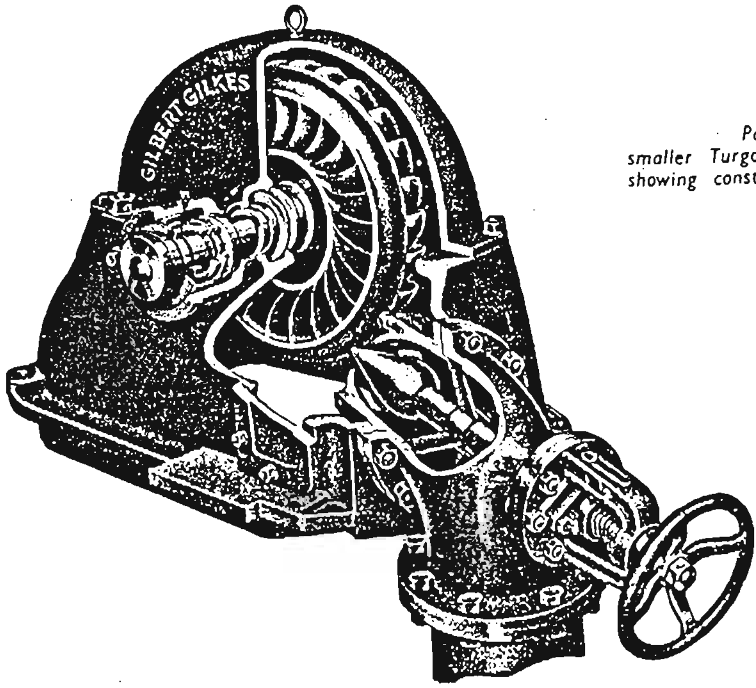


Figure 6. Section through the Cat Arm powerhouse, in Newfoundland, which is equipped with two Pelton turbines. The development has a 380 m head and a total rated capacity of 127 MW. (Newfoundland and Labrador Hydro, unpub. data).



Part section of a smaller Turgo Impulse Wheel showing constructional details.

Cast steel Turgo Impulse runner for a 4,600 B.H.P. turbine.

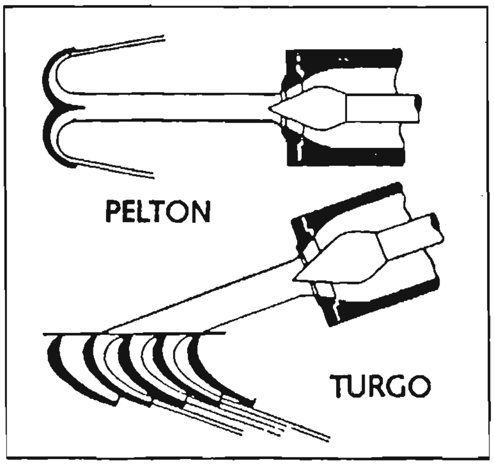
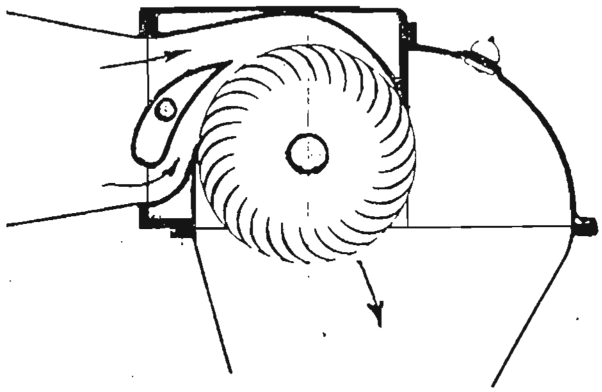


Figure 7. Illustration of a Turgo turbine.



Flow pattern in OSSBERGER cross-flow turbine; horizontal admission.

1. Casing
2. Guide vanes
3. Rotor
4. Main bearing
5. Corner casing
6. Air inlet valve
7. Draft tube
8. Reducer

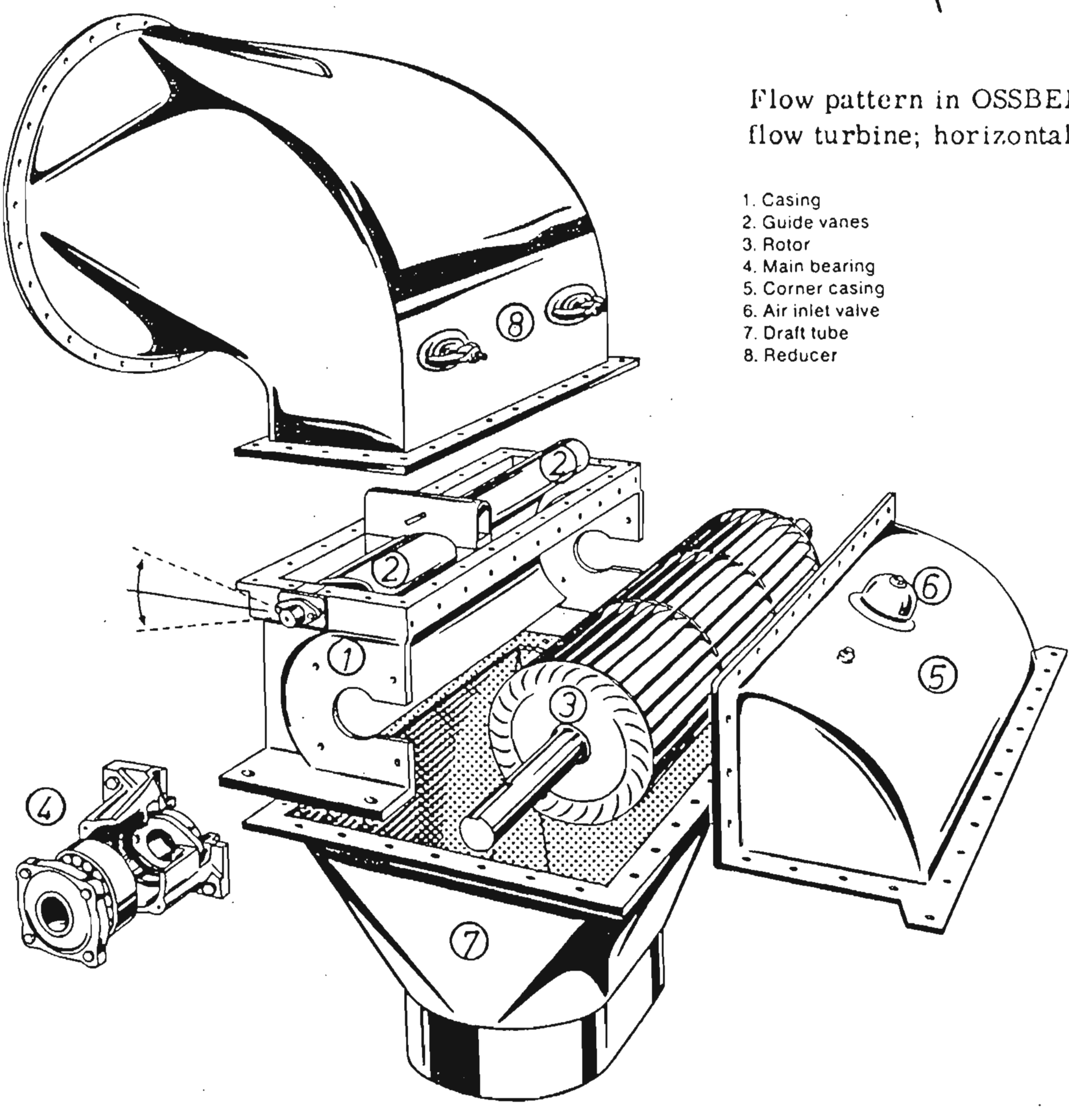


Figure 8. Illustration of a cross-flow turbine.

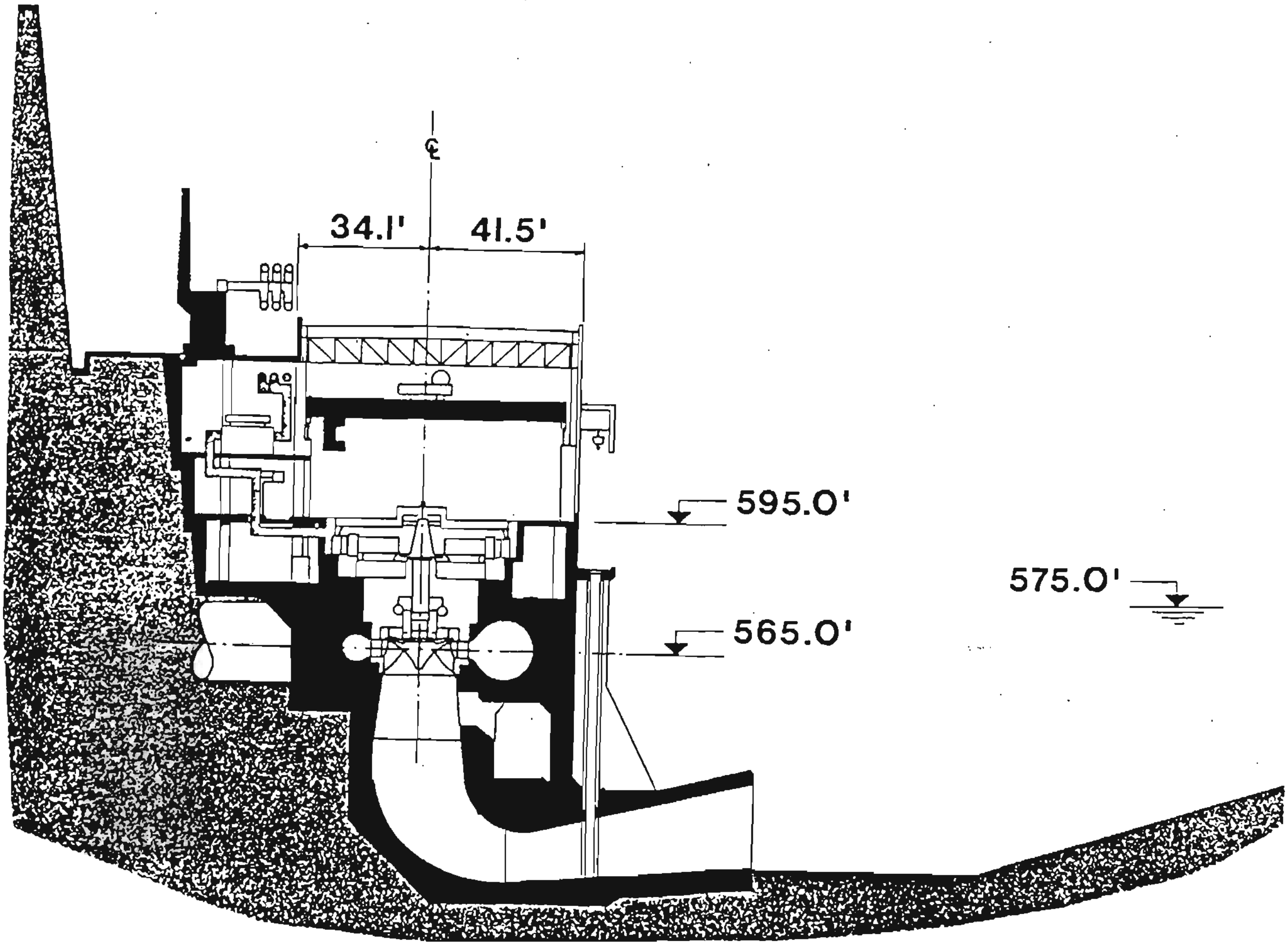


Figure 9. Section through the La Grande 3 powerhouse, in Quebec, which features 10 Francis units, a 79.2 m head, each turbine has a 5.6 m runner diameter with 13 blades. The total rated capacity is 190 MW. (Quebec Hydro, unpub. data).

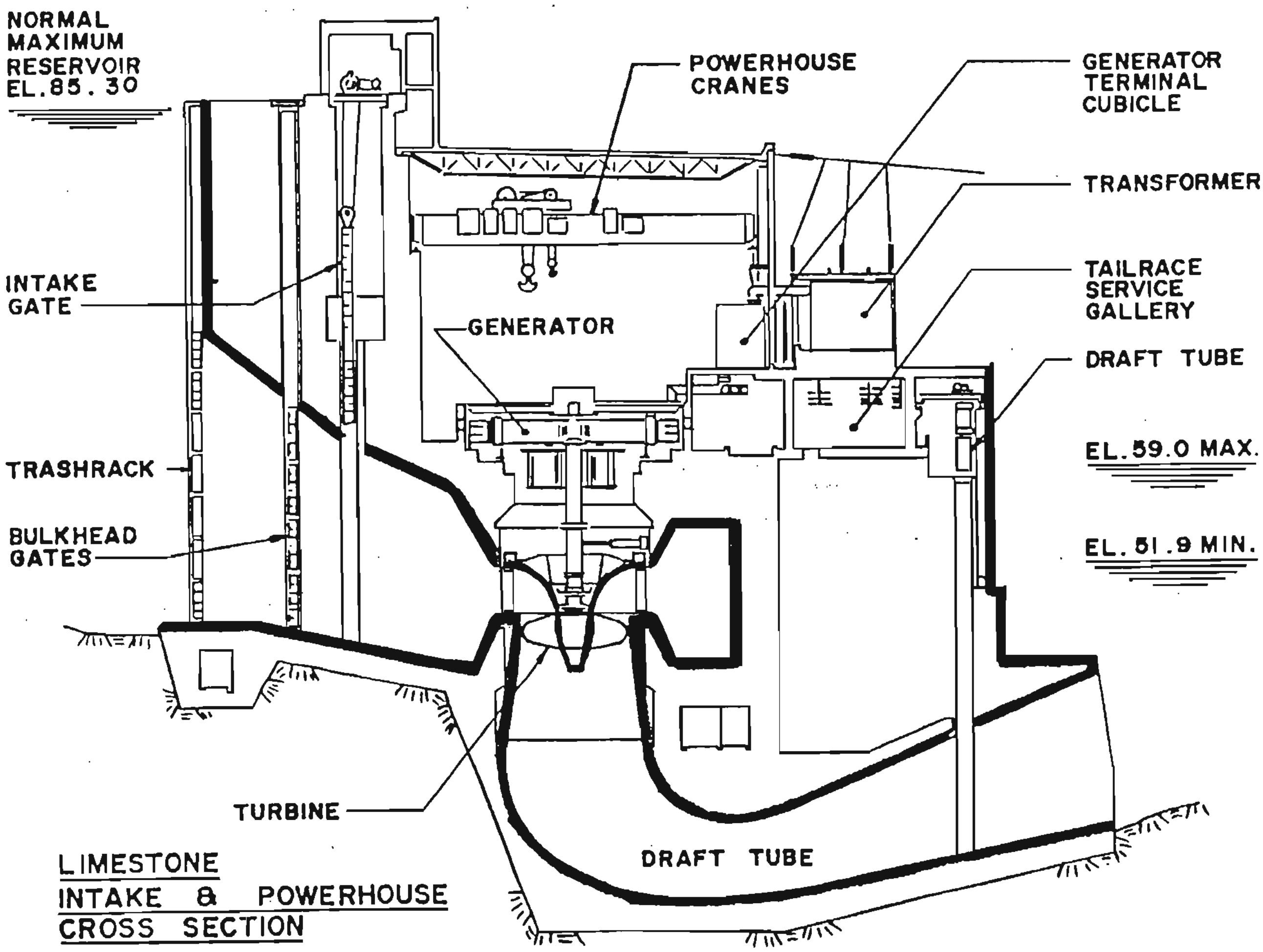


Figure 10. Section through the Limestone powerhouse, in Manitoba, which has a 27.6 m head and is equipped with 10 propeller turbines that have 7.93 m runner diameters and 5 blades. This powerhouse has a rated capacity of 125.4 MW. (Manitoba Hydro, unpub. data).

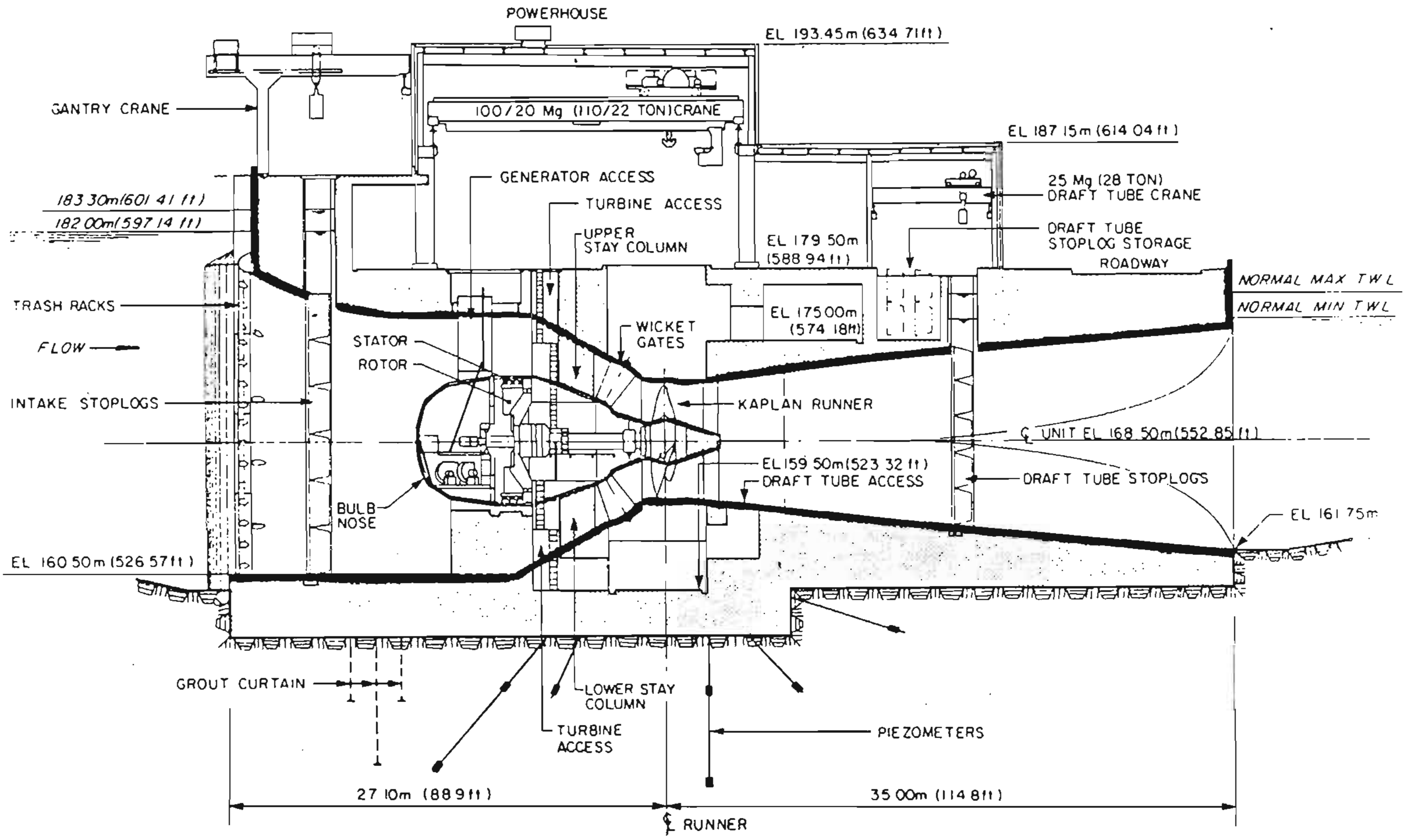


Figure 11. Section through the St. Mary's powerhouse, in Ontario, which has a 5.7 m head and is equipped with 3 bulb turbines. Each turbine has 4 blades and a 7.1 m diameter runner. (St. Mary's, Ontario, unpub. data).

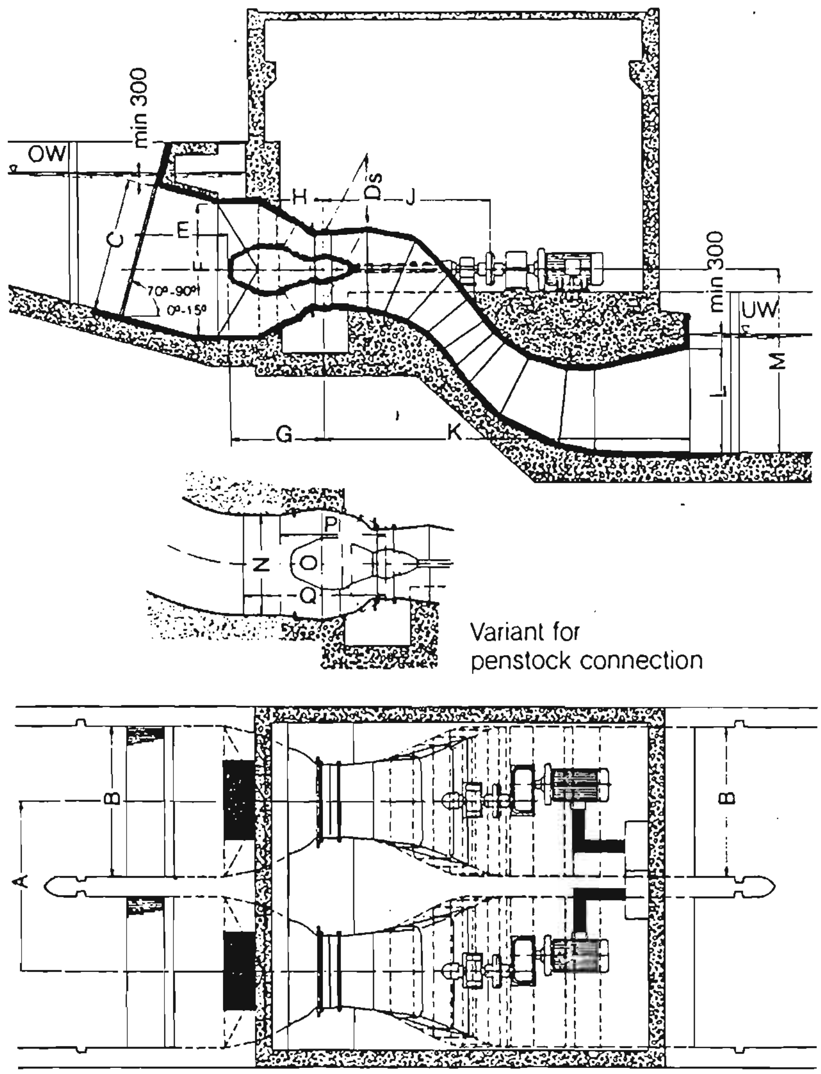


Figure 12. Plan and section through a typical "S" turbine.

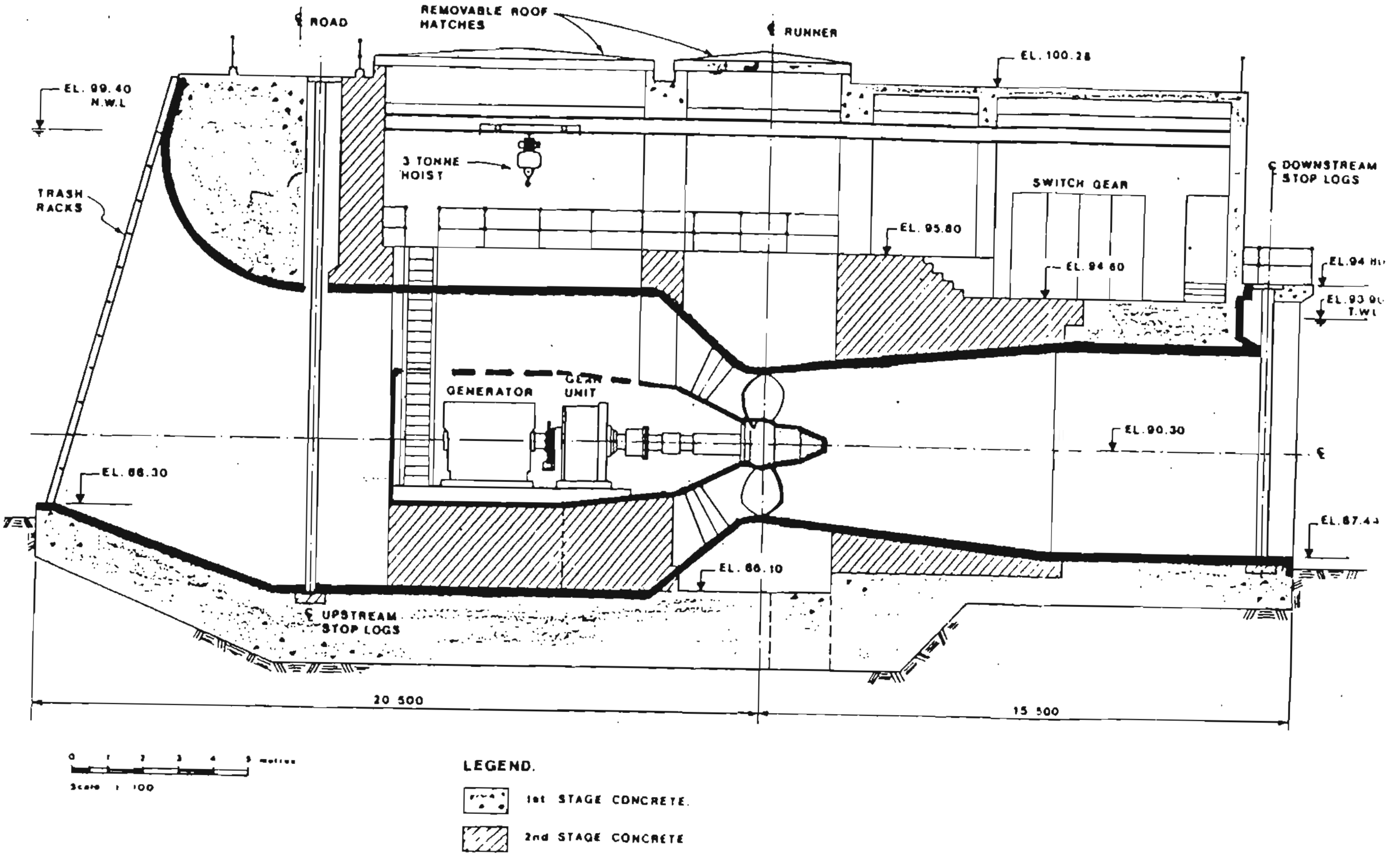


Figure 13. Section through the proposed Batawa powerplant, in Ontario. This powerplant will have 1 pit turbine that will have 3 blades and a 4.0 m diameter runner and will operate under a 5.2 m head. (Ontario Hydro, unpub. data).

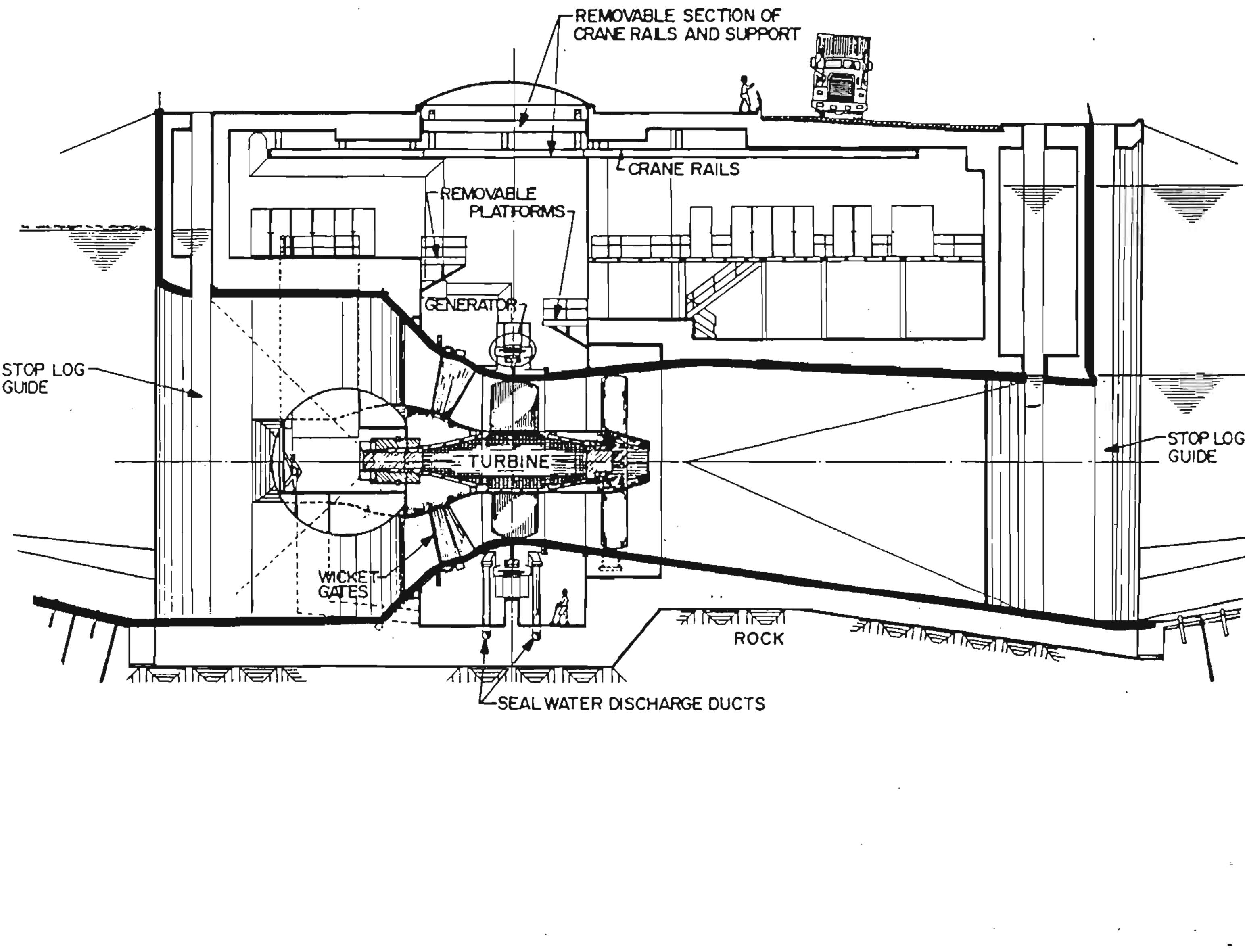


Figure 14. Section through the Annapolis powerplant, in Nova Scotia. There is a 17.4 MW Straflow unit that has 4 blades and a 7.6 m diameter runner. It operates under 5.5 m of head.

TURBINE RELATED FISH MORTALITY

TURBINE RELATED FISH MORTALITY

by

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ABSTRACT

Literature was reviewed to assess the factors affecting turbine related fish mortality. Various turbine related stresses and methodologies used in determining the effects of passage are discussed. The necessity of adequate controls in each test is also discussed. It is concluded that mortality is the result of several factors such as hardiness of study fish, fish size, concentrations of dissolved gases, and amounts of cavitation.

Comparisons between Francis and Kaplan turbines indicate little difference in percent mortality.

INTRODUCTION

Throughout the world, approximately 70 turbine mortality studies have been completed. Most of these involved Francis and Kaplan type turbines, while few involved tube, bulb or Ossberger types. Under the same siting conditions, little difference in mortality has been found between Francis and Kaplan units, but siting usually favours Kaplan types. Bulb types have been tested at relatively low mortality rates. Tube types, which should theoretically have rates comparable to bulbs, have shown higher mortality in two instances (Hogans and Melvin 1986; Ruggles and Palmeter 1989). This may be the result of siting conditions or differences in fish size. Figure 1 illustrates configurations of Francis and Kaplan turbines.

MECHANICS OF FISH PASSAGE THROUGH A TURBINE

Fish encounter a fairly consistent sequence of events when passing through turbines. They pass through the penstock or intake tube at a velocity of 1-6 m/s, which increases with narrowing of the passageway. Most fish occupy the upper levels of the conduit. At the end of the intake, fish enter the spiral case (a passageway circling around the turbine carrying fish and water at velocities of 3-9 m/s). They pass through the guide vanes, wicket gates and then enter the turbine at velocities of 12-15 m/s depending on the height of head. Velocities drop to 8 - 9 m/s after fish and water pass the runner blades or buckets and enter the draft tube, which flares toward the tailrace where velocities of about 2.4 m/s prevail. In the turbine, water and fish normally approach the runner at slightly higher velocities than that of the blades or buckets, thus the fish strike the blades rather than the blades striking the fish.

UNIFORM AND NON-UNIFORM STRESS

Brett (1957) hypothesized that turbine stress had a uniform effect upon all individuals. Therefore, he felt that a 10% loss was catastrophic because it meant that the uniform stress killed the weakest 10% and damaged the rest such that further natural stress would soon kill them. He based this theory on the assumption that principal turbine stress resulted from pressure change which, of course, would affect all fish uniformly. Although many biologists of the period agreed with Brett, evidence gathered in ensuing years disprove his contentions. For example, trout exhibited 50% mortality on their first trip through the turbine at the Lequille power plant. After a second trip through the turbines, the survival rate was again 50% suggesting that mortality was suffered by those individuals that encountered discrete mortality factors on each trip through the turbines. Those that did not make this encounter were as healthy after passage as before (Ruggles and Collins 1981).

PRESSURE EFFECTS

Apparently, the effects of pressure changes are species specific. Fish possessing a duct between the oesophagus and swim bladder are better able to accommodate pressure change. Exposure time to heavy pressure prior to release probably has a bearing upon effects. Fish adapted to atmospheric pressure are not affected by a sudden increase to three atmospheres followed by an almost immediate return to atmospheric values (Holmes 1952a).

SHEAR EFFECTS

Shear refers to the effect that two adjacent high velocity water flows have on fish situated in the boundary plane between the two flows. Evidence of this effect in turbine passage is unclear. Data indicate that shear damage may occur at velocity differences greater than 18 m/s (Theus 1972). It is not clear where such velocity differences occur within turbines, or if they occur.

HEAD

Head is the difference in elevation between forebay surface and tailwater surface. It governs the pressure against the turbine blades and the velocity of water approaching the runner. Head does not appear to have a significant effect upon fish mortality. Tests between Francis units with heads varying between 12 and 125 m show essentially the same mortality levels. Similarly, no relationship was found between mortality and head in 19 tests of Kaplan turbines operating between 6 and 34 m of head (Eicher 1987).

TAILWATER LEVEL

Elevation of the runner centerline with respect to tailwater surface level has been shown to affect mortality levels, presumably because of the resulting variation in subatmospheric pressure upon the runner blades or buckets. This also controls cavitation which is assumed to be damaging to fish.

TURBINE EFFICIENCY

Low mortality rates are found where turbine efficiencies are high. Efficiency and fish mortality curves tend toward flatness; hence it is difficult to exactly match the two. Curves developed by Cramer and Oligher (1961) for three salmonid species show greatest efficiency for a particular turbine at 70% wicket gate opening with least mortality at 75% opening (Figure 2).

DELAYED MORTALITY

Survival tests require the collection of delayed mortality data in order to determine the total magnitude of effects. In almost all delayed mortality studies, the greatest mortality normally occurs on the first day, followed by a sharp drop off on ensuing days. Eighty-two percent of the delayed mortalities occurred at Cushman #2 powerhouse during the first day of holding, followed by 10.5% on the second day and 6.8% on the third day (Cramer and Oligher 1961). This pattern concurs with most studies involving injury to fish.

INJURY IDENTIFICATION BY SOURCE

It is difficult to pin point the source of turbine related injuries because it is normally impossible to observe fish passing through turbines and because many types of injuries are assumed to be caused by various factors. For example, bulging or protruding eyes have been attributed to mechanical, pressure, and shear effects. Wide, unexplained variability in results of replicate studies at a single plant, cause one to question the accuracy of non replicated tests.

CONTROLS

When conducting turbine mortality tests it is necessary to use control lots of fish which experience every part of the test procedure as the test fish, with the exception of passing through the turbine. Some types of tests, such as the downstream recovery method, are based on comparisons of test and control fish.

TYPES OF TESTS

Most earlier tests were made using a large net to strain the entire flow leaving the turbine. These exploratory tests were designed to assess damage from various sources. A variation of this is use of fyke nets which sample a known portion of the discharge. These versions of the downstream recovery method are used most frequently to assess mortality when the source of mortality is less important than the overall effect of the turbine. An extension of this is the adult recovery system in which fish are marked as juveniles, passed through the turbines, and recovered as adults when they return to spawn (Holmes 1952b).

The large net method has the advantage of providing information on individual fish. However, it has disadvantages. It is costly to make even one large net. It has an unmeasurable source of error because the test fish are exposed to the stresses of both turbine passage and collection in the net. The combined effects of passage through the turbine and collection are greater than the separate effect. Controls do not adequately account for this (Bell 1967). Fyke net sampling has the same problem. Downstream recaptures and adult returns are the least costly and factor in predation and other environmental effects, but they do not provide information on individual causative factors and require extremely careful use of controls.

SOURCES OF MORTALITY

As mentioned previously, it is difficult to determine the sources of mortality because of observational limitations. Some indices are available from correlations between mortality levels and operating conditions. An examination of 21 studies using Francis units produced a correlation coefficient of 0.73 between peripheral runner speed (speed at which the runner periphery moves) and mortality (Eicher 1987) (Figure 3). Collins and Ruggles (1982) found a relationship between wicket gate opening and mortality in Francis units, but it was not strong.

No strong relationship between mortality and any single factor has been discerned for Kaplan units. However, some inferences can be made from the examination of features. In large Kaplan turbines such as found in Columbia River plants, fyke netting has shown that the majority of fish descend through the inlet in the upper water column (Figure 4), thus descending through the turbine near the hub. There are few areas of apparent danger within these turbines because the leading edges of blades are gross, rounded and move at slow speeds. The only suspect areas are discrete cavitation spots which occur at certain generation stages, and the clearance between the blade tip and the distributor ring (Figure 5). High water velocities may carry fish into this opening causing mortalities and injuries. Approximately 15 % of the fish arrive at the turbine blade in an area that would cause them to enter this clearance gap (Long 1975). Similar mortality rates have been documented for Kaplan turbines (Holmes 1952; Schoeneman *et al.* 1961).

TIME DEPENDENT TURBINE COMPARISONS

Replicate turbine tests have been conducted at a number of locations but some replicates were several years apart. In 4 instances, the later tests showed higher mortality rates. The reasons for this are not clear except that there was a tendency to use larger, more vulnerable fish in the second sets of tests.

At the Leaburg plant on the McKenzie River in Oregon, the Oregon Game Commission conducted tests in 1958 (using direct recovery in a large net) of rainbow trout immediately after turbine passage. Calculated mortality was 4.7% (Oregon Game Commission 1958a). Also at Leaburg, the Oregon Department of Fish and Wildlife, a successor agency, tested the same turbines using the downstream recovery method in 1982. Recoveries, approximately 180 miles downstream, indicated turbine mortality of 28.1% (Oregon Department of Fish and Wildlife 1984a).

At Foster Dam on the South Santiam River in Oregon, the U.S. Army Corps of Engineers, probably using large net recovery, found an adjusted mean mortality of 11.2%. At virtually the same time, Fish Commission of Oregon biologists, using draft tube nets and scoop traps, developed an "apparent" turbine mortality of 4.2 to 6.3% using the same fish species (yearling chinook and steelhead) (Wagner and Ingram 1973; Bell and Bruya 1981).

At Bonneville Dam, on the Columbia River, Harlan B. Holmes, U.S. Fish and Wildlife Service, performed extensive turbine mortality studies from 1938 to 1948. Using over 1.5 million juvenile chinook salmon in an adult return test, Holmes estimated mortality as ranging from 11 to 15% (Holmes 1952). In 1954, Kingsley G. Weber, also of the U.S. Fish and Wildlife Service at Bonneville Dam, obtained a 4% mortality estimate when using a fyke net to sample the turbine discharge. His experiment made use of 21 tests and involved 16,800 fish (Weber 1954).

At Elwha Dam on the Elwha River in 1954, D.E. Schoeneman and C.O. Junge of the Washington Department of Fisheries utilized the downstream sampling method to recover chinook salmon released into the turbines and tailrace. Recovery traps were more than a mile downstream. Essentially zero mortality was found (Schoeneman and Dilley 1954). In 1985, R.C. Wunderlich and S.J. Dilley, of the U.S. Fish and Wildlife Service, repeated Schoeneman and Junge's work at Elwha, using essentially the same techniques and sites except the fish were coho and larger than the chinook of the earlier tests. Mortalities ranged from 12.2 to 29.5%. Similar results were produced using adult return data (Wunderlich and Dilley 1985).

At Condit Dam on the White River in Washington, Schoeneman, Meekin and Junge of the Washington Department of Fisheries, obtained a mortality estimate of 30% in 1954 using the downstream recovery method and chinook fingerlings (Schoeneman, *et al.* 1955). In 1984, at Condit Dam, David Seiler, also of the Washington Department of Fisheries, obtained 76% mortality using methods similar to the 1954 tests, but with coho smolts.

Walterville Dam on the McKenzie River in Oregon, was the site of two tests; one in 1958 conducted by the Oregon Game Commission and one conducted in 1982 by its successor, the Oregon Department of Fish and Wildlife. The first test used the large net direct type of test and rainbow trout in two stages. The first stage resulted in a mortality rate of 2.5% while the second resulted in 7.5% mortality (Oregon Game Commission 1958b). In the 1982 tests, chinook salmon smolts were used in a downstream sampling system, with recoveries of test and control fish in a turbine bypass trap about 170 miles downstream. A mortality rate of 13% was established (Oregon Department of Fish and Wildlife 1984b). The Walterville tests paralleled those cited earlier for Leaburg. In both cases, the later tests showed greater mortalities than the earlier ones, however, some reasons for this exist. The earlier direct tests involved smaller rainbow trout which survive turbine exposure better than large smolted juvenile salmon. Also the later downstream recovery tests were flawed in application in a way that could have indicated greater mortality.

FACTORS AFFECTING THE ACCURACY OF TURBINE STUDY RESULTS

Various factors can greatly influence turbine mortality at a given power plant. Different species of fish demonstrate widely differing susceptibilities to injury. Salmonids are fairly tough, whereas, allosids are not. Small fish survive these tests better than large fish because small fish tend to be more flexible and have a lesser tendency to resist currents. Fish condition is also important. Poor health can cause greater than typical mortalities and confuse results, even though controls are used. Temperature and oxygen concentrations may also be confounding factors. The expansion of small amounts of gas is enough to stop the heart (Harvey 1963; Rucker 1972; Ruggles 1980), therefore, concentrations of dissolved gases in the presence of subatmospheric pressures within turbines may bias results. Therefore, procedures and safeguards to prevent confounded results are a necessary part of comprehensive turbine tests. Examination of the procedures and results of the 70 odd turbine mortality studies revealed that most had experimental shortcomings.

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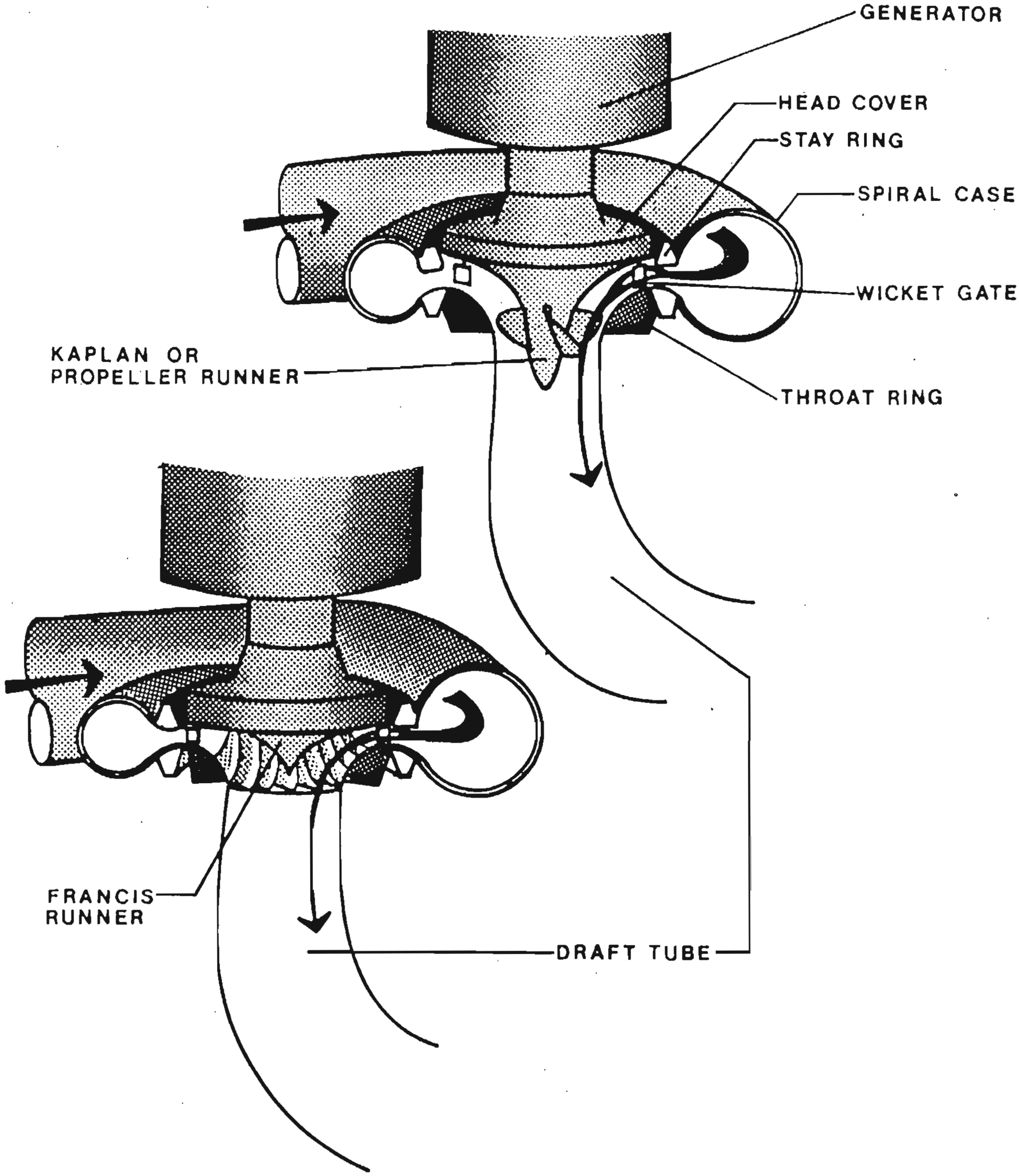


Figure 1. Details of Francis and Kaplan turbines showing flow paths (Ruggles 1980).

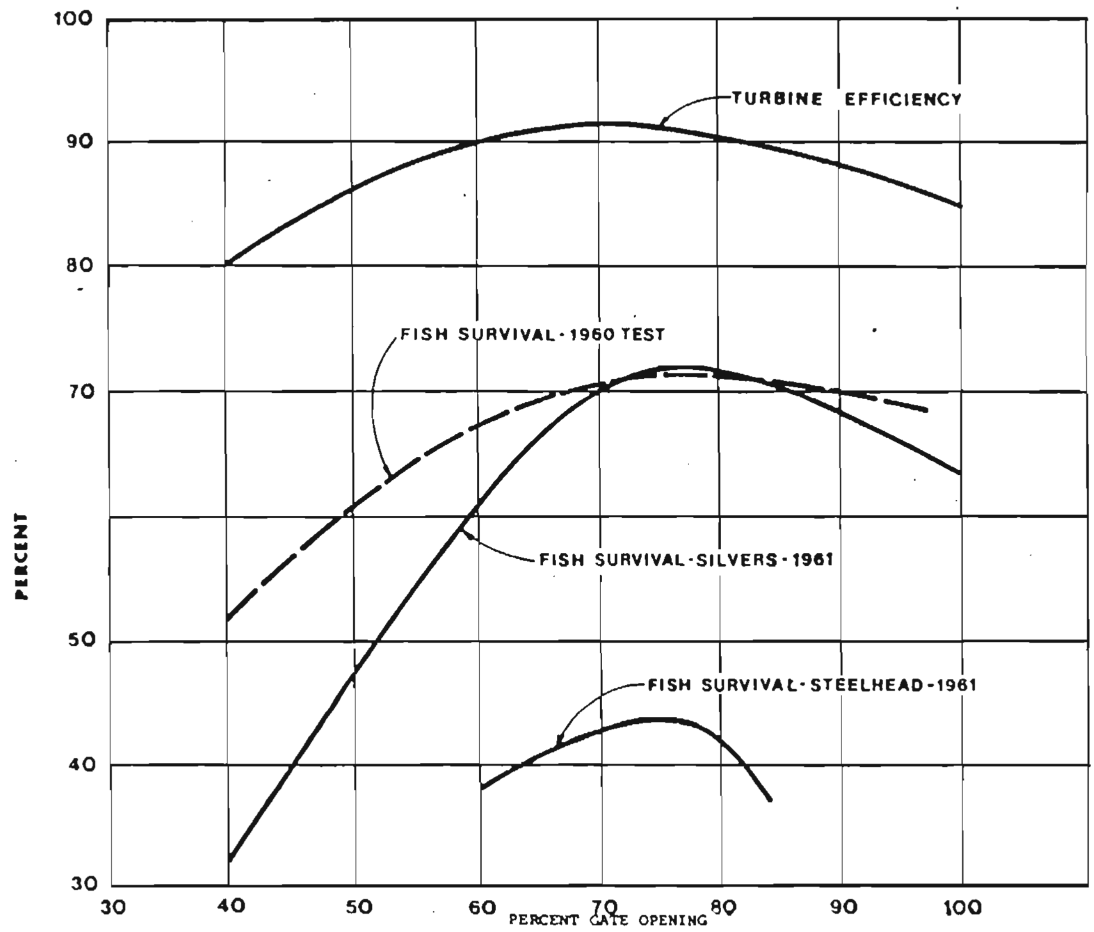
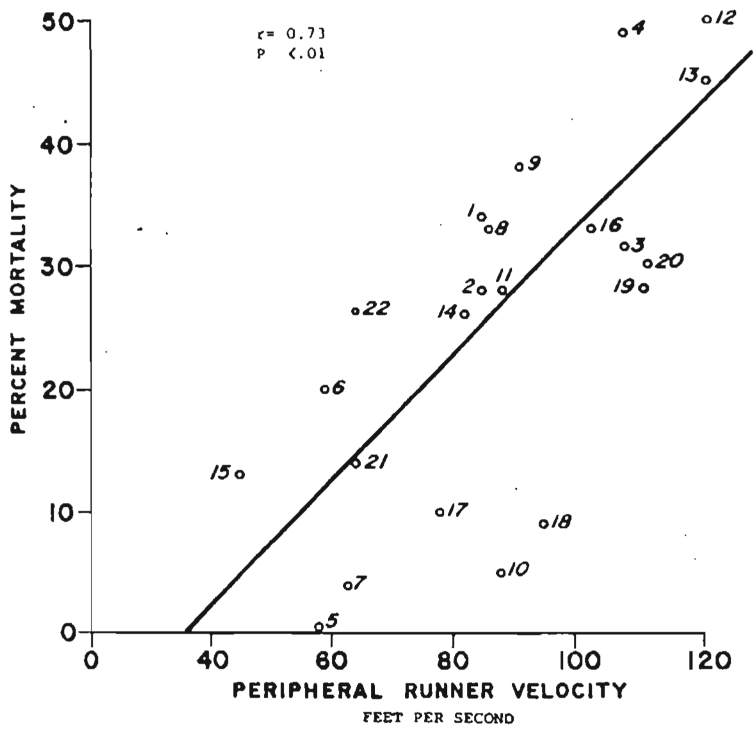


Figure 2. Percent efficiency of a turbine and percent survival of fish passed through it at various gate openings (Cramer and Oligher 1961).



Number Key

1. Baker -- sockeye
2. Baker -- coho
3. Cushman -- 1960
4. Cushman -- 1961
5. Elwha -- 1954
6. Elwha -- 1983
7. Faraday
8. Glines — 1954
9. Glines — 1983
10. Leaburg — 1958
11. Leaburg — 1983
12. Lequille -- 1980
13. Lequille -- 1981
14. North Fork
15. Publishers
16. Puntledge
17. Ruskin
18. Seton Creek
19. Shasta — January
20. Shasta -- November
21. Sullivan -- chinook
22. Sullivan -- steelhead

Figure 3. Relationship between peripheral runner velocity and fish mortality passed through Francis turbines.

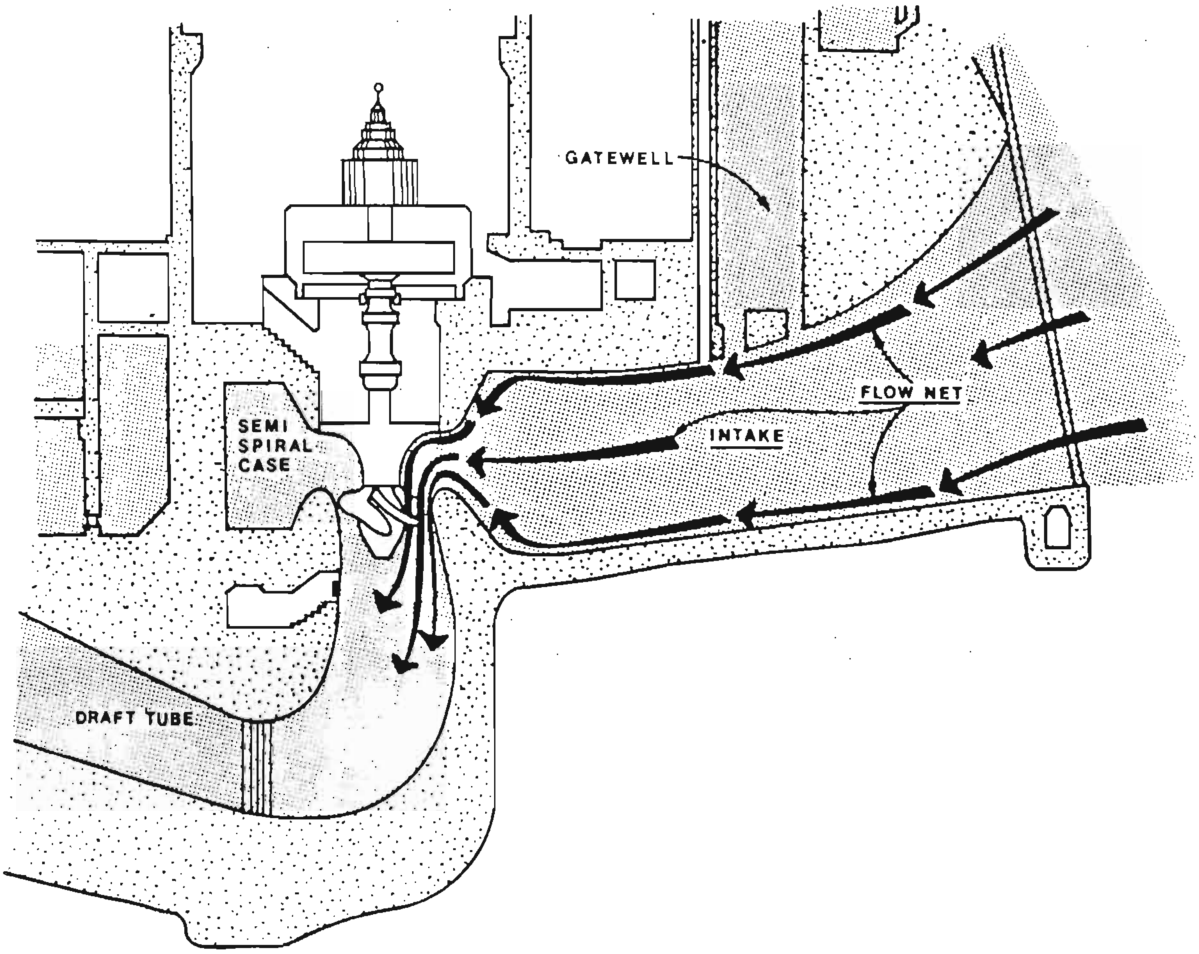


Figure 4. Section through a large Kaplan turbine showing flow paths (Long and Marquette 1967).

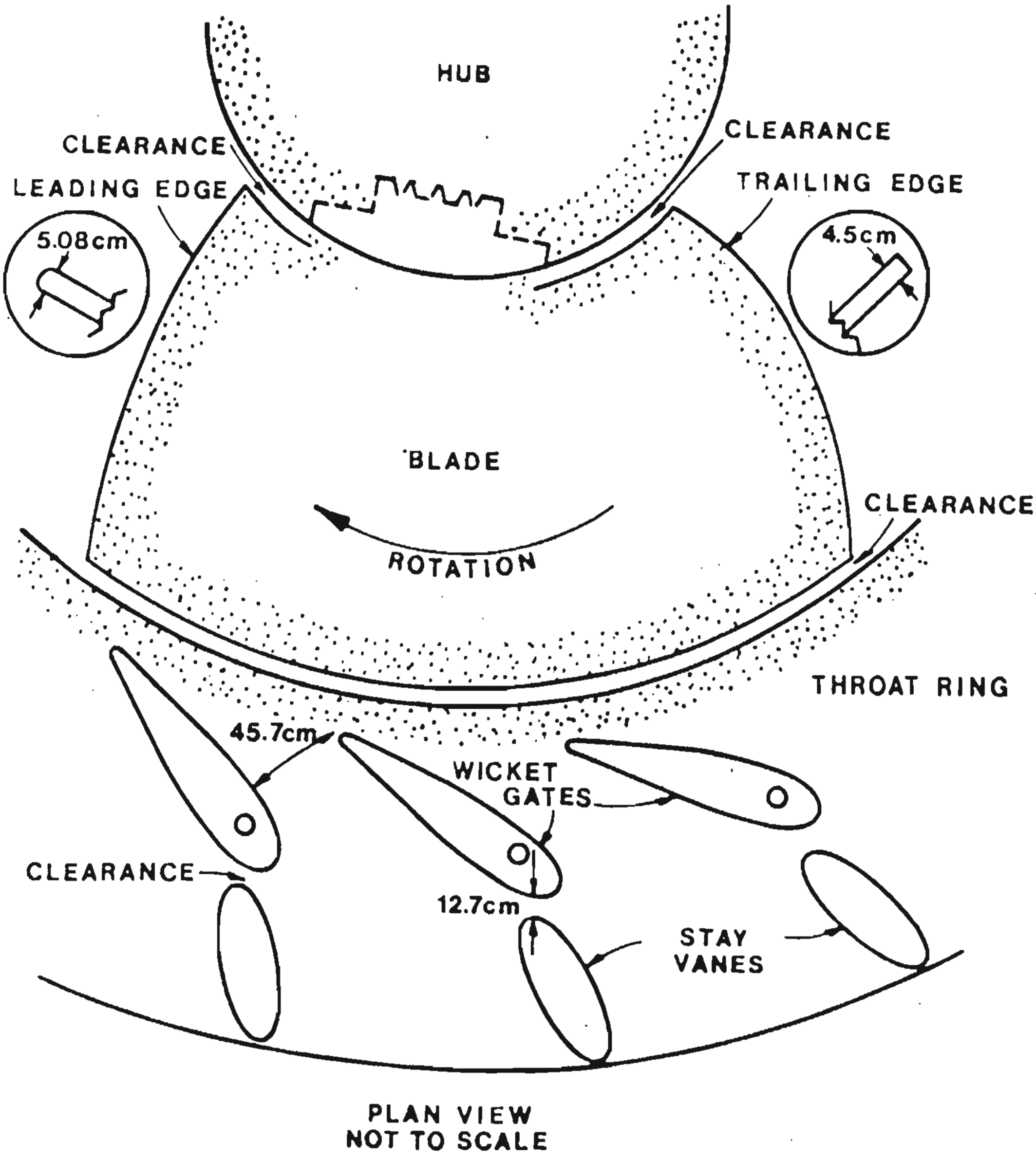


Figure 5. Top view of a Kaplan runner blade showing the clearance between the hub and runner blade, the wicket gates and the blades, and the guide vanes and the wicket gates (Long and Marquette 1967).

A NEW TECHNIQUE FOR ASSESSING FISH PASSAGE SURVIVAL AT HYDRO POWER STATIONS

by

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ABSTRACT

The HI-Z Turb'N Tag (U.S. Patent No. 4,970,988) recovery method is presented as a new technique that was successfully used at ten hydrostations to determine turbine or spillway passage survival of fish. Fish were recovered quickly from the tailrace (mean <10 minutes) after being tagged and released into a turbine. The tag buoyed fish to the surface and allowed for ≥90% recovery in most tests. The technique had minimal effect on the well being of both hardy (channel catfish, *Ictalurus punctatus*) and sensitive (juvenile American shad, *Alosa sapidissima*) species and provided an opportunity to examine recovered fish for injuries and retain them (up to 72 h) to assess possible delayed effects. The Turb'N Tag-recapture technique overcomes most of the logistical problems associated with conventional methods (netting, radio telemetry, mass mark-recapture) to determine turbine passage survival. The technique can also be used to assess effects of spill and fish bypass structures.

INTRODUCTION

The impact of hydro power facilities upon fish movement becomes a concern when the facilities are on rivers, that have runs of anadromous fish, or are targeted for restoration of species. There are also similar concerns for resident species that may make downstream movements. Various techniques have been employed to characterize the extent of injury and mortality incurred by fish passing through operating turbines. Sampling techniques and results have been presented in several reviews (Eicher Associates 1987; EPRI 1986, 1988; Ruggles 1980; Ruggles *et al.* 1990; Turbak *et al.* 1981). These reviews indicate that many sampling methods do not allow quantifications of fish injury and mortality solely due to turbine passage. The purpose of this paper is to present a new tag recovery technique that overcomes most problems in assessing the survival of fish upon turbine passage. The HI-Z Turb'N Tag (U.S. Patent No. 4,970,988) enables investigators to recover test fish from the tailwater of a power station after turbine passage. The technique induces minimal stress on test fish and eliminates the deployment of large recovery nets. This technique is also applicable for assessing injury and mortality associated with passage through spill gates and fish diversion facilities. This technique was used by Heisey *et al.* (1992) and Mathur and Heisey (1992) to estimate turbine passage survival of juvenile American shad (*Alosa sapidissima*), channel catfish (*Ictalurus punctatus*), and bluegill sunfish (*Lepomis macrochirus*).

Spilling water, screening or bypass facilities are recommended by regulatory agencies to minimize fish mortalities at hydroelectric power stations. These facilities can be expensive and may inflict injury and mortality when constructed without the benefit of reliable data (Ruggles *et al.* 1990). Therefore, it is of paramount importance that a reliable technique be employed to determine the effects of passage through hydro turbines.

PREVIOUS TECHNIQUES

Netting, radio telemetry and mass mark-recapture have been the principal methods utilized to assess injury and mortality associated with passage at hydro stations. Although these methodologies have merits at some facilities they suffer from deficiencies and can provide ambiguous data. Nets deployed in the tailwaters to recapture turbine passed fish inflict injury and mortality; debris can further compound this problem. Fitting recovery nets with water filled collection boxes decreases the negative effects of a recovery net, however sensitive species and life stages can still be injured. Recovery nets also require special engineering and equipment to function in high discharge areas. They are costly to construct, maintain, and often require structural modifications to the power station.

Tracking radio tagged specimens after power station passage can provide reliable information for specimens that are not subject to predation and are normally active. However, telemetric monitoring is labour intensive, particularly if one wishes to assess long-term effects (several days) of passage. Telemetric results may be confounded by:

(1) radio signals that are lost after station passage;

(2) moving radio signals that result from predation or dead specimens moving in water currents; and

(3) stationary signals from live fish that move into confining cover.

If the fish is not physically recovered, the extent of injuries cannot be determined, nor can the fish be held for careful observation. In addition, few radio tags are recovered and thus contribute substantially to the cost of a study.

Marking fish with conventional tags (PIT tags, stains, brands, and coded wire tags) can be effective but normally requires large numbers of specimens to be marked, extensive recovery facilities and sampling programs. Mass marking fish has limited application for resident species when downstream recovery facilities are the primary means for recapturing marked specimens. Injury and mortality associated solely with turbine passage is obscured by additional injury and mortality inflicted by predators in the tailwater and in the river between test and recovery sites. Additionally, some injury and mortality may be associated with recovery facilities.

HI-Z TURB'N TAG TECHNIQUE

The HI-Z Turb'N Tag (Turb'N Tag) was first utilized to assess injury and mortality incurred by young American shad passed through a hydro turbine on the lower Susquehanna River. Thus far it has been utilized on six species and at ten hydro stations. The Turb'N Tag is constructed of brightly coloured latex and, prior to inflation, is pear shaped and approximately 35 mm long and 13 mm wide (Plate 1). When fully inflated it measures approximately 75 mm in length and 50 mm in diameter, and weighs approximately 2 g (Plate 2). A Turb'N Tag is secured externally to the fish with a small stainless steel pin and a plastic disc. The pin is injected through the musculature of the fish with a modified ear piercing gun. The number of tags applied depends upon size and swimming strength of the fish. One tag is sufficient to retrieve fish less than 180 mm in length, while three tags may be necessary for fish >300 mm. When conducting studies in areas with high discharges or large tailwaters, a small neutrally buoyant radio tag may be used in combination with the Turb'N Tags. The radio tag is cylindrical, approximately 30 mm in length, 10 mm in diameter and weighs 1.7 g. Signals are emitted through a 27 cm long wire antenna. The radio tag can be inserted into the fishes' stomach or attached externally with a stainless steel pin.

After a short observation period the tagged fish is introduced into the intake area of an operating unit through a specially designed induction apparatus consisting of a small holding basin (approximately 75 litres) attached to a 7.6 or 10.2 cm supply-delivery line. The Turb'N Tag inflates shortly after passage and buoys the fish to the surface. The buoyed fish is netted from the tailwater by a tracking crew usually less than ten minutes after it was released.

After recovery the fish are placed in an onboard holding tank, the tags carefully removed, and the fish is examined for injury and scale loss. Because fish are usually recovered and tags removed within minutes after release, potential stress to the fish associated with the tags is minimized.

Finally, the fish can be transported to an onshore tank, or a floating net pen and held for delayed mortality assessment. Control fish are handled the same as test fish except they are released directly into the discharge of the operating test turbine.

PERFORMANCE OF THE TURB'N TAG

The tag and recovery procedure has been tested on juvenile American shad, juvenile and adult smallmouth bass (*Micropterus dolomieui*), channel catfish, bluegill sunfish, juvenile blueback herring (*Alosa aestivalis*), and Atlantic salmon smolts (*Salmo salar*). Tests were conducted at ten hydro stations located in eastern USA and Canada (Table 1). Performance criteria used were the recovery rates and times for different turbine types and operational conditions.

Smallmouth bass (238 test and 130 control), 100 to 305 mm long were passed through a facility with vertical Francis turbines equipped with double or quad-runner blades (Table 1). The capacity of each unit was approximately 25 m^3/s. Tests were conducted at worst case operating conditions: wicket gate opening of 60% and high water temperatures (20.5 to 27°C). Post-passage conditions were discernible for approximately 90% of the fish passed through the turbines. The release until recovery time ranged from 1 to 188 minutes, with a mean of less than 12 minutes. Most fish were recovered from the tailrace shortly after release but some remained inside the discharge tunnels (50 m long) thereby lengthening recovery times.

Channel catfish (177 test and 50 control) 105 to 345 mm long were passed through an adjustable horizontal propeller type turbine (S-Type bulb). The power station has two fixed and one adjustable units. The hydraulic capacity of each unit is approximately 21 m^3/s. Tests were conducted at the adjustable unit with turbine blade settings of 13 and 28° (near minimum and maximum). Tests were conducted during the summer when water temperatures ranged between 20 and 23°C. Ninety percent of the test fish were recovered and the status was discernible for an additional 3% of the fish passed through the turbine (Table 1). Recovery time averaged less than 4 minutes (range = 1-32 min.).

Bluegill (105 test and 94 control) 80 to 204 mm long were passed through the same turbine as channel catfish. Tests were conducted only at a turbine blade setting of 13°. Eighty-eight percent of the bluegill passed through the turbines were physically recovered and the status was discernible for another 2% (Table 1). Bluegill were all recovered within 8 minutes after release.

Bluegill (61 test and 59 control) were also tested at another facility with three Kaplan turbines. Tests were conducted at a normal discharge rate of 38 m^3/s per unit. Eighty-four percent of the fish passed through a unit were physically recovered from the tailwaters (recovery time range = 1-452 min.). Recovery time averaged 18 minutes upon excluding three specimens with the highest rates. These fish were buoyed to the surface shortly after release but were not readily accessible to the recovery crew.

Catfish species (62 test and 52 control) were tested at the latter facility. Fish ranged from 160 to 305 mm in length. Ninety one percent of the fish were recovered. Recovery time averaged 11 minutes (range = 1-128 min.).

Juvenile American shad (72 test and 40 control) ranging from 90 to 145 mm were passed through a horizontal Francis unit of a large peaking hydroelectric station (512 MW). Each unit discharges approximately 142 m^3/s. Tests were conducted at water temperatures of 8.5 to 12.5°C. Seventy-six percent of the specimens were physically recovered (Table 1). Post passage status was known for 93% of the specimens and recovery time averaged 5 minutes (range = 1-19 min.).

Juvenile American shad (299 test and 300 control), 95-140 mm long were passed through Kaplan and mixed-flow turbines at another large (418 MW) hydro station. Each unit discharges approximately 241 m^3/s. Water temperatures ranged from 9 to 22.2°C. Fish were tested under three operating conditions: Kaplan and mixed-flow units normal operation; and mixed-flow unit vented operation. Recovery rate was high with 91 - 97% of the fish physically recovered (Table 1) and recovery times ranging from 1-35 minutes, while the mean time was <10 minutes.

Juvenile American shad (25 test and 25 control) ranging in size from 87 to 114 mm (total length) were passed through a station in Canada with propeller type turbines (Terry), with fixed blades. Each unit has an optimal discharge of 137 m^3/s. At the time of testing water temperature was 23.8°C. Recovery rate of specimens released through a turbine was 92% (Table 1). Recovery time ranged from 1 to 12 minutes. Most specimens were recovered in less than 5 minutes of release.

Juvenile American shad (200 test and 180 control) were sent through a station with single and double runner Francis turbines. Each unit has an optimal discharge of 99 m^3/s. Both units were tested at 100% gate setting. Water temperatures at time of testing ranged from 9.0° to 17.0°C. Eighty percent of the specimens were physically recovered at the single runner unit. Post passage status was known for 87% of the specimens (Table 1). Recovery time averaged 3 minutes (range = 1-14 min.). Seventy-six percent of fish were physically recovered for the double runner unit. Post passage status was known for 79% of the specimens. Average recovery time was 4 minutes (range = 1-17 min.).

Juvenile American shad (320 test and 320 control) ranging from 55 to 110 mm were passed through a facility with two vertical propeller type turbines, one fixed and one Kaplan. Fish were introduced at two gate settings of 35% and 100%. The discharge was approximately 44 and 119 m^3/s at these respective stage settings. Tests were conducted at water temperatures ranging from 11 - 25°C. Recovery rates ranged from 74 to 82% and most fish were retrieved within 10 minutes after passage (range = 1-76 min.) (Table 1).

Juvenile blueback herring (125 test and 125 control) ranging in size from 77 to 105 mm (total length) were also tested at another facility with adjustable, propeller-shaped runners (Kaplan turbines). Fish were released at a wicket gate setting of 77% and water temperatures of 14 to 18.5°C. Eighty-four percent of the herring were physically recovered from the tailrace. Post passage conditions were discernible for 87% of herring passed through a turbine (Table 1). Average recovery time for test fish was 5 minutes (range = 1-18 min.). In addition to herring being passed through a turbine, 110 test and 110 controls were passed over a 4 m high spillway. Ninety-four percent were recovered and the status was discernible for another 3% (Table 1). Recovery time averaged 3 minutes (range = 1-12 min.).

Two year old Atlantic salmon smolts (100 test and 100 control) ranging in size from 145 to 358 mm were introduced into a 152 m straight walled concrete conduit (Log Sluice). Fish plunged from a height of 9 m into the tailrace. Water temperatures at testing ranged from 10.0 to 11.5°C. Ninety-five percent of the fish were physically recovered (Table 1). Post passage status was known for 99% and recovery time averaged 13 minutes (range = 3-49 min.).

DISCUSSION

Rapid recovery of most passed fish with minimal handling stress is of paramount importance in the assessment of mortality attributable to turbine or spillway passage. The Turb'N Tag and recovery procedure satisfied these criteria at all test power stations. Percent recovery was high yet recovery time was short. Of the more than 4,000 fish tagged and released the resulting status for over 90% was known within minutes.

Low recovery rates of marked fish can statistically invalidate the estimates of turbine passage survival (Turbak *et al.* 1981; Kynard *et al.* 1982; Ruggles *et al.* 1990). A low recovery rate of fish can virtually eliminate the possibility of assessing long-term effects of turbine passage. Therefore, the ability to recover most test specimens has practical implications. A statistically pre-determined valid sample size can be established. Our studies suggest that a sample of 100 fish may be sufficient to obtain the same degree of statistical reliability achieved by conventional mark-recapture studies normally involving several thousand or even millions of test specimens. Obviously, the efforts necessary to collect and recover several thousand test specimens substantially increases manpower needs and expenses. It may be impossible to obtain a large number of test specimens due to the restoration status of a species or because it has a special protection status.

Recovery of most test specimens allows determination of the type, extent and location of injuries. All recovered fish can be carefully examined and injuries reliably quantified. Associations between specific injuries and specific features within turbines requires the collection of sufficient data. This information may lead to minimizing injuries through minor structural or operational modifications.

The Turb'N Tag-recovery technique also provides an avenue for transferring turbine survival data between hydroelectric sites. If data become available from a sufficient number and variety of hydroelectric projects with different turbine types, flow characteristics, etc., trends may be ascertained. This may in turn, save time, reduce costs, and improve the quality of predictions necessary to assess potential effects of turbine passage on fish populations. Tailrace netting and mass mark-recapture methods can be difficult to implement at several power stations. Consequentially, conventional methods may require more time to gather a large diverse database on turbine passage survival.

The Turb'N Tag recapture technique proved to be flexible relative to species, turbine types, spillway configurations, station operating conditions, and size of test specimens. Because the technique worked extremely well on juvenile American shad, a species sensitive to handling and tagging, it will be applicable to many species. Although not field tested on very small (≤50 mm) or large sized fishes (>400 mm) it is anticipated that it will perform well for a large size range of fish. Future experiments are planned to determine the technique's feasibility on large adult fishes, particularly American shad. Finally, since most specimens are recovered quickly they can be exposed to turbine passage several times thus providing useful information in evaluating cumulative effects of more than one hydro station.

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Table 1. **Recovery rates and times of fish equipped with HI-Z Turb'N Tags after passage though turbines or spillways at ten hydro power stations.**

Study	Turbine Type or Bypass	Discharge Unit (m^3/s)	Species	Size (mm)	No. Fish	Physically Recovered %	Known Status %	Recovery Time (min) Range	Recovery Time (min) Mean
1	Double Runner Vert. Francis	25	Smallmouth bass	120 - 305	100	80	85	1 - 188	4
	Quad Runner Vert. Francis	25	Smallmouth bass	100 - 305	138	91	94		
2	S-Type bulb Blade Setting 13°	11	Channel catfish	146 - 345	102	90	94	1 - 32	4
	S-Type bulb Blade Setting 28°	17	Channel catfish	105 - 323	75	91	93	1 - 10	2
	S-Type bulb Blade Setting 13°	11	Bluegill sunfish	80 - 204	105	88	90	1 - 8	3
3	Kaplan	38	Bluegill	110 - 205	61	84	84	1 - 452	18*
	Kaplan	38	Catfish sp.	160 - 305	62	91	91	1 - 128	11
4	Vertical Francis	142	American shad	90 - 145	72	76	93	1 - 19	5
5	Mixed Flow Normal	241	American shad	95 - 140	100	91	92	1 - 16	7
	Mixed Flow Vented	241	American shad	95 - 140	99	94	97	2 - 25	9
	Kaplan	241	American shad	95 - 140	100	97	99	1 - 35	5
6	Terry Fixed	137	American shad	87 - 114 Total Length	25	92	92	1 - 12	3
7	Francis - Single	99	American shad	85 - 163	100	80	87	1 - 14	3
	Francis - Double	99	American shad	85 - 163	100	76	79	1 - 17	4
8	Kaplan Adjustable (100%)	119	American shad	55 - 110	100	76	76	3 - 13	5
	Kaplan Adjustable (35%)	44	American shad	55 - 110	100	81	82	2 - 7	4
	Kaplan Fixed (100%)	119	American shad	55 - 110	120	74	74	1 - 76	10
9	Kaplan Adjustable (77%)	43	Blueback Herring	77 - 105 Total Length	125	84	87	1 - 18	(5)
	Spillway	1			110	94	97	1 - 12	(3)
10	Ice-Log Sluice	21	Salmon	145 - 358	100	95	99	3 - 49	13

* Excluding three fish which were inaccessible for a while; mean = 5 minutes.

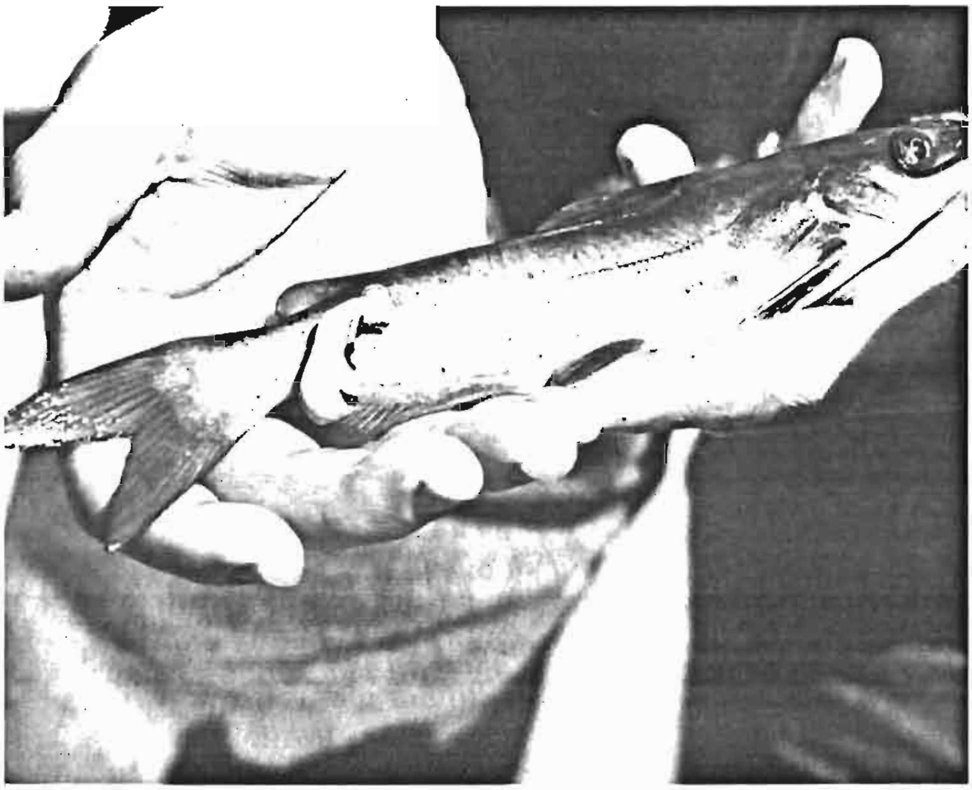

Plate 1. Turb'N Tag prior to inflation attached to test specimen.

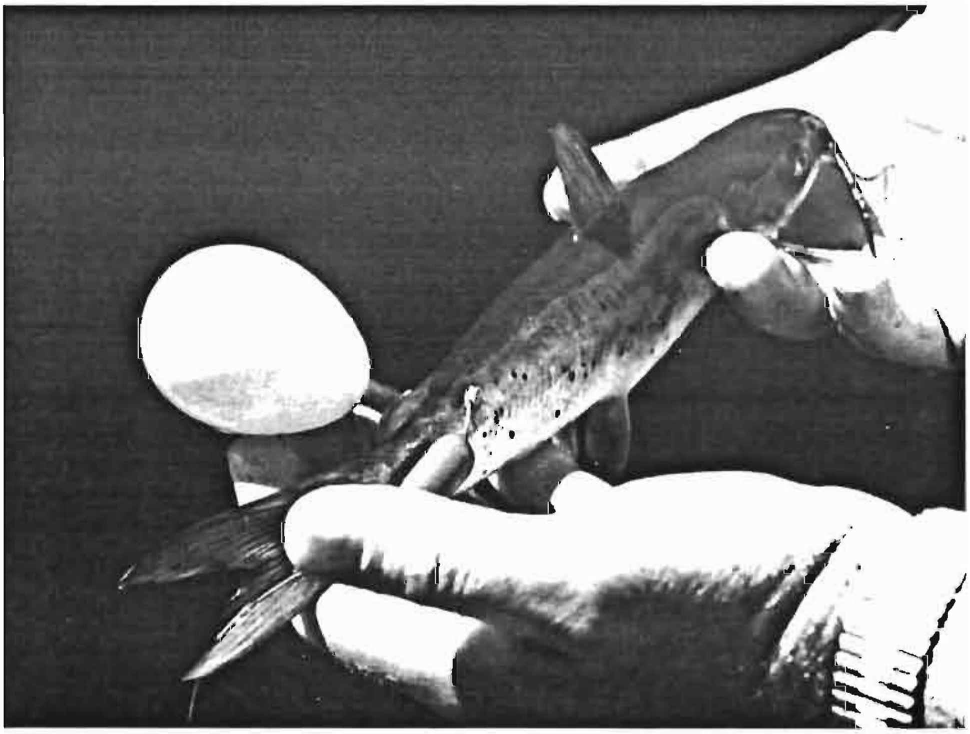

Plate 2. Turb'N Tag after inflation.

EFFECT OF STRESS ON TURBINE FISH PASSAGE MORTALITY ESTIMATES

by

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ABSTRACT

Tests were conducted with juvenile alewife to determine the effects of four experimental protocols upon turbine fish passage mortality estimates. Three protocols determined the effect of cumulative stresses upon fish, while the fourth determined the effect of long range truck transportation prior to release into the penstock or tailrace. The wide range in results were attributed to the presence or absence of additional stress factors associated with the experiments. For instance, fish may survive passage through a turbine, or non-turbine related stresses imposed by the investigator, however, when both are imposed, the cumulative stresses may be lethal. The impact of protocol stress on turbine mortality estimates becomes almost exponential after control mortality exceeds 10%. Valid turbine related mortalities may be determined only after stresses associated with experimental protocol are adequately reduced. This is usually indicated by a control mortality of less than 10%.

INTRODUCTION

Fish bypass systems installed to provide fish protection at turbine intakes sometimes inflict more fish mortality than passage through turbines (Ledgerwood *et al.* 1990). It is important, therefore, to accurately measure turbine induced fish mortality to realistically evaluate the trade off between this source of mortality and the mortality that may be an unavoidable consequence of many fish exclusion systems presently in use at hydroelectric turbine intakes.

The manner in which fish mortality estimates are derived can have a profound effect on estimates of fish passage mortality. For instance, Ruggles and Palmeter (1989) derived two quite different estimates of turbine induced juvenile alewife (*Alosa pseudoharengus*) mortality from two different experimental protocols. One estimate of fish mortality (66%) was derived from the release of test and control juvenile alewives and their subsequent recovery in a fish recapture net that strained the entire flow from the turbine discharge. A second estimate of fish mortality, derived from the recapture of naturally migrating alewives that had become entrained by the turbine flow, indicated an average mortality of less than 14 %.

Sometimes fish mortality estimates using the same experimental protocol can result in quite different estimates of turbine induced fish mortality. Hogans (1987) and Hogans and Melvin (1986) report on two years of research involving the use of acoustically tagged adult shad (*Alosa sapidissima*) to estimate mortality during turbine passage at the Annapolis tidal powered turbine in Nova Scotia. In the first year of studies the mortality due to turbine effects was estimated to be 46.3%, after adjusting for a control mortality of 20.5%. The second year results indicated that the turbine induced mortality had dropped to 21.3 %, after adjusting for a control mortality of 4.5 %.

One explanation for the difference in fish mortality estimates is the impact of sub-lethal stress imposed by experimental protocol. The objectives of the present study were to identify the impact of stress on estimates of immediate mortality of juvenile alewives passing through a relatively small, medium head, tube turbine. The experiments were conducted at the Fourth Lake Hydroelectric site (Figure 1) during the fall juvenile alewife migration period in 1987, 1988 and 1989.

SITE LOCATION AND TURBINE DESCRIPTION

The Fourth Lake Hydroelectric development is located on the Sissiboo River approximately 30 km upstream from the village of Weymouth, Nova Scotia. The generating plant is located below an earth filled dam at the outlet of Fourth Lake. Flow is derived from a drainage area of 260 km^2. Water from the reservoir is delivered to the turbine through a 82 m long steel lined concrete penstock. An overall layout of the Fourth Lake hydroelectric development showing the fish introduction and recapture locations is presented in Figure 2.

The single horizontal "S-turbine" was designed by Escher-Wyss and built by Dominion Bridge-Sulzer. The turbine develops a maximum of 4,000 hp under a rated head of 22.7 m and a flow of 15.1 m^3/s.

The following are pertinent specifications:

- Type of Turbine	Tube (S-Turbine)
- Rated Head	23 m
- Rated speed	360 RPM
- Number of Wicket Gates	13
- Number of Runner Blades	6
- Runner Diameter	1.65 m
- Hub Diameter	0.79 m
- Peripheral Runner Velocity	32.1 m/s
- Discharge	15 m^3/s
- Rated Output	3.1 MW
- Runner Elevation in relation to Tailwater	-1.1 m

METHODS

Three different experimental protocols were used to derive turbine induced mortality estimates for alewives. The three protocols involved two different levels of stress associated with the capture, marking and releasing of experimental and control lots of fish. A third group was made up of alewives that were entrained by the flow entering the penstock and were not handled prior to their recapture after passing through the turbine. A fourth experimental protocol was used for comparison based on results from similar experiments conducted in 1987 by Ruggles and Palmeter (1989). The four protocols were as follows:

Protocol 1 - Entrained juvenile alewives experiencing no handling, marking or release stresses prior to passage through the turbine. The entrained alewives were the progeny of adult alewives placed in the headpond each May during the three years experiments were conducted.

Protocol 2 - These were juvenile alewives seined from the headpond, held for one to three weeks prior to their use as test or control fish, distinctively marked and then released into the penstock (test fish) or into the exit of the draft tube (control fish).

Protocol 3 - These were Protocol 2 fish that were subjected to an additional stress immediately prior to their release as test or control fish. The additional stress involved holding the alewives in unaerated garbage cans for 5 minutes prior to their release. The stress was non-lethal and fish which lost their equilibrium were removed prior to their release and the totals adjusted accordingly.

Protocol 4 - This protocol from previous research reported by Ruggles and Palmeter (1989), involved juvenile alewives captured in the fall of 1987 by dip-net in a fishway on the Tusket River, transported by tank truck over a distance of about 60 kilometres, and held in floating net pens in the Fourth Lake headpond. After a period ranging from a few days to three weeks of acclimation, fish were marked and released into either the penstock or draft tube.

Experimental fish were released into the penstock during various test periods and recovered in a fish recapture net that strained the entire tailrace discharge. Control fish were treated identically to test fish and were introduced near the exit of the draft tube. Tests revealed that control releases in the exit of the draft tube and those released just upstream of the recapture net suffered the same mortality. Thus control releases were available "to correct" for handling and fish recapture mortality.

Juvenile alewives were seined from the Fourth Lake headpond and held in two 800 litre circular fish tanks supplied with 18 litre/min. of water from the headpond by means of a 5 cm submersible pump. Attempts to hold test and control alewives were unsuccessful, therefore, an evaluation of delayed mortality was not attempted.

Test and control alewives were marked by using a fluorescent powder spraying technique

(Phinney *et al.* 1967). Fish were marked immediately prior to their release into the penstock or draft tube. Upon recovery in the fish recapture gear, fish were sorted into live and dead groups. The alewives were not measured prior to release so as to avoid additional handling stress. All recaptured alewives were measured and examined for injuries.

The introduction of test and control fish was coordinated with a previously arranged schedule for operating the turbine at an 80 % wicket gate opening (usual operating position). Prior to the test routine, all fish and debris were removed from the fish recapture gear. After the turbine had been running for about 15 minutes, test and control fish were introduced. After a period of from one to two hours, the turbine was shut down and fish were removed from the fish recapture gear.

Test and control fish were introduced by means of a 10 cm diameter plastic pipe. A 220 litre capacity wooden release box was fastened to the top of the narrower pipe with a rubber plug inserted to retain water while the fish were added (Figure 3). Fish and water were released by pulling the rubber plug. The release box and pipe were flushed with 70 litres of water as the box drained. Introductions of all test and control fish were carried out using identical systems and procedures to ensure valid control results. Test fish were introduced into the penstock through the gate slot at the entrance of the penstock. Control fish were introduced through a gate slot near the exit of the draft tube tunnel. Staining and introduction mortality over the two years of testing averaged 0.6%.

The entire flow from the turbine discharge was strained by a modified fyke net made of 1.3 cm stretched mesh nylon netting connected to a floating live box by a 20 cm diameter flexible hose (Figure 4). Steel framing was anchored to the stream bed about 30 m downstream of the exit of the draft tube tunnel and the netting was attached with 9.5 mm shackles through the headropes. Gaps below and at the sides of the framing were screened with 1 mm mesh to ensure complete straining of the discharge.

Towards the end of the 1988 fall testing season a deterioration in netting efficiency was noted that resulted in higher fish mortality during recapture. Prior to the 1989 test period, much of the netting material was replaced in the fish recapture gear in an effort to reduce this source of recapture mortality.

Turbine induced mortality of test alewives was estimated by comparing the ratio of the fraction of recaptured test fish to the fraction of recaptured control fish by the following formula:

$$M = (1 - St/Sc) \times 100$$

M = percent of fish killed by turbine effects only
St = fraction of live fish recovered in a test group
Sc = fraction of live fish recovered in the accompanying control group.

This method of calculation is the same as the relative recovery rate method (Ricker 1945, 1948) and the first capture history protocol of Burnham *et al.* (1987).

In addition to recapturing test and control fish, the recapture net also caught juvenile alewives that were entrained by the turbine flow originating from the Fourth Lake reservoir.

Estimates of turbine mortality for entrained fish were calculated by dividing the total number of dead fish captured by the total number of captured fish. These mortality estimates did not correct for any mortality inflicted by the recapture process. Control releases of dead and live alewives showed that they were equally vulnerable to recapture.

Data analysis was carried out using the Statistical Package for the Social Sciences (SPSS/PC + V 2.O) program on a personal computer. Computer files containing the length frequencies of all recaptured fish, injury frequencies and mortalities were prepared. Initial stages of analysis included statistical tests to investigate deviations in length frequency between live and dead recaptures. All percentage data were arcsine transformed prior to statistical analysis.

Factor analysis was used to investigate correlations between injury types and other variables such as delay in recapture and fish length. Injuries were examined separately and in groups. Because there were so few observations for each specific type of injury, dead fish were grouped into two categories: "injured dead" (dead fish with a visible injury) and "uninjured dead" (dead fish with no visible injury). Multiple regression and comparison of means (t-tests) were the primary statistical methods used.

RESULTS

In 1988, both live and dead control releases of non-stressed alewives (Protocol 2) were recaptured at an average rate of 80%. Regression analysis involving water temperature, fish length and headpond elevation with mortality and percent severed failed to establish relationships at the 0.05 probability level. The "uninjured" dead component of the mortality, however, was significantly correlated with both water temperature and fish length. Seven tests conducted with the unstressed alewives are summarized in Table 1. The mean estimated mortality for these unstressed alewives is 16.4 ± 6.4%. Non-stressed alewife control mortality averaged 17.8 ± 21.6%.

The five tests conducted with experimentally stressed alewives (Protocol 3) are summarized in Table 2. Regression analysis involving water temperature, fish length and headpond elevation with mortality and injury type failed to reveal significant relationships. The mean estimated mortality for these data is 38.9 ± 6.5%. Control mortality for stressed alewives averaged 28.5 ± 18.8%.

On eleven occasions during the fall of 1988, estimates of turbine induced mortality of naturally migrating juvenile alewives could be calculated (Protocol 1). Table 3 summarizes the available information on these fish and presents estimates of turbine induced mortality. Mortality inflicted by the recapture gear accounts for some of the fish killed. The average uncorrected mortality for these fish was 41.5 ± 14.8%. No significant relationships existed between fish length, water temperature, headpond elevation and mortality or percent severed. However, these variables were significant with the "uninjured" dead component of the entrained alewives. The mean length of the dead alewives (82.7 ± 11.5 mm) was significantly ($P \leq 0.05$) smaller than the mean length of the live alewives (90.5 ± 9.6 mm).

The 12 observations on entrained alewives (Protocol l) obtained during the fall of 1989 field season are summarized in Table 4. A total of 9,233 entrained alewives are included in these observations. The mean turbine induced mortality (uncorrected for recapture mortality) is 17.5 ± 6.0 %. The mean length of the dead alewives (96.1 ± 2.1 mm) was significantly smaller than the mean length of the live alewives (98.4 ± 2.5 mm) ($P < .05$).

COMPARISON AMONG PROTOCOLS

Table 5 presents a summary of alewife tests conducted in 1987 and 1988 where releases of test fish (introduced into the penstock) and control fish (released into the exit of the draft tube) were used to estimate turbine induced mortality. It was thought that improved alewife handling and release procedures adopted in 1988 might result in lower estimated mortality than was found in the 1987 tests. This is in fact what happened. Intermediate mortality estimates were obtained when the 1988 alewives were subjected to an oxygen stress by holding test and control fish in unaerated water prior to their release into the penstock and draft tube. The use of controls failed to correct for the differences in fish condition in the three groups.

Field observations during 1987 noted that the introduced test and control alewives were in poor condition prior to their release. Pre-test handling left the fish in a severely stressed condition. In 1988, fish handling and introduction procedures were changed which resulted in the 1988 alewives exhibiting very high vitality immediately prior to testing. Control mortality for 1987 alewife tests was 37.3% compared to 1988 control mortalities for stressed and unstressed fish of 28.5 and 17.8%, respectively.

Table 6 summarizes the results obtained from observations of turbine mortality derived for entrained alewives in 1987, 1988 and 1989. The high estimated mortality in 1988 (41.5 %) compared to the 1987 estimate (14.0 %) was completely unexpected. During the course of the 1988 tests, field observations noted that the fish recapture gear on several occasions was not fishing properly. The deterioration was attributed to clogging of the net by algae. On some occasions, large quantities of leaves interfered with the flow in the live box. For this reason, the 1988 entrained alewife mortality estimate is considered invalid.

After replacing the netting in the recapture gear, the entrained alewife mortality dropped to 17.8% in 1989.

Although 1987 and 1989 entrained alewife mortality estimates are low, they are still an over estimate of turbine induced mortality because there is no correction for mortality inflicted by the recapture gear. Field observations in 1988 noted that there was greater recapture mortality than in 1987. Because of the high mortality estimate in 1988 it was felt that some attempt should be made to correct for recapture mortality of entrained alewives.

By examining the numbers of severed alewives from test releases of stressed and unstressed fish, a correction factor for recapture mortality of entrained fish was derived. The derivation of the correction factor assumes that the chance of being struck by the turbine is constant. Hence, there should be the same percent of severed fish in the population regardless of the stress level. However, with increasing stress levels there is a greater number of non-severed dead fish. A control mortality for each entrained group can be estimated using the equation from the regression line of the proportion of dead experimental test fish which are severed with control mortality. The correlation coefficient for the regression was -0.848 and P=0.001. The equation from this regression is:

% of severed dead fish = (transformed control mortality x -1.08) + 57.13.

By transposing, an estimate of control mortality for entrained alewives was derived as follows:

$$\text{predicted control mortality} = \frac{[\text{sine}(\%\ \text{severed dead} - 57.13)]^2}{-1.08}$$

A corrected turbine induced mortality estimate for entrained alewives was calculated by subtracting the predicted control mortality from the mean uncorrected mortality estimate and is tabulated below:

Year	Total Dead Severed (%)	Estimated Control Mortality (%)
1987	56.7	0.005
1988	19.5	32.6
1989	39.8	7.6

Year	Uncorrected Turbine Mortality (%)	Corrected Turbine Mortality (%)
1987	14.0	14.0
1988	41.5	8.9
1989	17.5	9.9

On the basis of this analysis, entrained alewife mortality is believed to be between 9 and 14%. For the purpose of subsequent analysis, the simple mean of these estimates (11 %) is used.

IMPACT OF STRESS ON MORTALITY ESTIMATES

Multiple stress resulting from turbine passage plus fish recapture may have confounded results making it impossible to use controls in estimating correction factors for the three test groups. The proportion of "uninjured", dead fish was highest in the 1987 tests, intermediate in the stressed 1988 tests and lowest in the unstressed 1988 tests. This portion of the mortality probably reflects juvenile alewives that were killed by the fish recapture gear. Thus, even though alewives may survive turbine passage, some are in such poor condition that they are unable to survive the additional stress of recapture. Control fish, on the other hand, only contend with the stress inflicted by the recapture gear. The overall vitality of the experimental fish, therefore, has a profound impact on the estimate of turbine induced mortality.

A variety of stresses associated with the conduct of turbine fish passage experiments can cause substantial differences in fish mortality estimates. These stresses are brought about by such things as capture, transportation, marking, release, and recapture of experimental and control fish. These stresses can be non-lethal and the stressed condition may be unapparent. Often, however, stresses associated with experimental protocol are reflected in the mortality of control fish.

Stress elicits immediate neuroendocrine responses which induce metabolic and osmotic disturbances (Parker *et al.* 1959; Bouck and Ball 1966; Barton *et al.* 1980). For example, the exposure of fish to air or to unaerated water induces a significant increase in blood glucose (Mazeaud *et al.* 1977). Barton *et al.* (1986) examined some of these physiological responses in chinook salmon juveniles after two or three consecutive handling stresses and found that the responses were greater after two and three stresses than after a single stress. The ultimate response to stress is death.

A wide biological variation is seen in the response of individual fish to stress. Some strains of domesticated rainbow trout for example are particularly adapted to stress factors associated with aquaculture. The better adapted fish are to stress associated with the experimental protocol, the more reliable the mortality estimate will be. Thus, some species or populations of fish are not as vulnerable to errors in mortality estimates as others.

Fish health affects the response to stress. Fifty percent of unhealthy chinook salmon fingerlings stressed three times died within 3-6 hours after the third stress compared with no mortalities in two other similar groups of healthy fish. The unhealthy fish had a chronic fin rot condition accompanied by an infection of the coldwater disease bacterium *Cytophaga psychrophila* (Barton *et al.* 1986).

Various indiscriminate stresses act cumulatively. Thus, the presence of one stress can compromise the ability of fish to respond to additional stresses. When the cumulative effect of stress is manifested in a mortality of 10 %, slight additional changes can cause catastrophic losses among the remaining fish (Brett 1958). Hence, when control mortality in turbine fish passage tests reach a level of 10 %, the resulting mortality estimate is questionable. In the case of fish that are particularly sensitive to the stresses associated with turbine fish passage experiments, great care must be taken to arrive at a valid estimate of turbine induced mortality. A varying component of the turbine mortality includes the integrated effect of several components of stress not directly related to passage through the turbine. This portion of the mortality manifests itself in the "uninjured dead" component of the observed turbine mortality.

Figure 5 shows the estimated turbine mortality of alewives plotted against a scale of stress imposed by the various experimental protocols used to derive the mortality estimates. The average control mortality of each protocol is used as a measure of stress. The entrained fish represent zero control mortality and a turbine induced mortality of 11 %. They are the lowest on the stress scale, having only the recapture stress to be integrated with the turbine passage stress. The 1987 alewives which were transported from the Tusket River are the highest on the stress scale (data from Ruggles and Palmeter 1989).

With zero stress imposed by experimental protocol, there is no effect on the mortality estimate. As protocol stress increases the measured effect (control mortality) rises. However, control mortality does not rise at the same rate as the overall mortality of the test fish, resulting in an overestimate of turbine induced mortality. The more stress imposed by the experimental protocol, the greater the error. The impact of protocol stress on turbine mortality estimates for alewives appears to be curvilinear, showing little impact until control mortality exceeds 10%. At this level of stress the overestimate rises almost exponentially so that by the time control mortality is about 35%, the mortality estimate is six times as great as it was when control mortality was less than 10%.

Even when control mortality is low, an error may be introduced because of the effect of non-lethal cumulative stresses associated with control and test fish. Control fish may suffer stress associated with recapture that is insufficient to cause mortality. This recapture stress may be lethal to test fish which have survived turbine passage because of the cumulative effect of stress imposed by turbine passage and recapture. This source of error will also increase as the overall stress imposed by the experimental protocol increases.

Results described from these turbine fish passage experiments conducted over a three-year period show great variation in fish mortality estimates. The variation in mortality estimates is believed to be caused by the presence or absence of additional stress factors associated with the conduct of the fish passage experiments. Only by reducing stress associated with experimental protocol can the true extent of turbine fish passage mortality be estimated.

The following factors influence the degree of stress imposed by experimental protocol:

- choice of fish (species, race, size, health),
- method of capture,
- method of transportation,
- holding facilities,
- marking procedures,
- use of anaesthetic,
- release procedures,
- recapture procedures, and
- environmental conditions.

All of the above factors must be considered when planning turbine fish passage experiments with a view to reduce sources of stress that may compound errors in turbine mortality estimates. Even if we could measure the effect of each of these separate stresses, we cannot confidently predict their combined effect. The outcome of one stress influences the effect of a subsequent one. Each individual stress may be sublethal but the cumulative effect, including the sublethal effect of turbine passage, can be lethal. All we can do is to reduce as many factors as possible that might influence the degree of stress imposed by the experimental protocol. The best indication of success or failure in controlling stress imposed by experimental protocol is control mortality. It should not exceed 10%.

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Table 1. Summary of 1988 unstressed alewife tests (Protocol 2).

Test	Date	Temp (°C)	Type [1]	Number Released	Number Severed	Whole Dead [2] Injured	Whole Dead [2] Uninjured	Total Dead	Total Live	Mean [3] Length (mm)	Uncorrected [4] Mortality (%)	Estimated [5] Mortalty (%)
2	19/09/88	16.0	T	99	9	9	2	20	66	95.4	23.3	12.7
			C	102	0	7	0	7	51	97.4	12.1	
3	20/09/88	15.0	T	99	6	3	1	10	55	97.8	15.4	10.3
			C	101	0	3	2	5	83	96.6	5.7	
4	21/09/88	15.5	T	100	4	10	5	19	64	95.0	22.9	15.6
			C	101	0	3	5	8	84	96.2	8.7	
5	21/09/88	15.5	T	100	8	6	4	18	56	94.0	24.3	19.7
			C	101	0	1	4	5	83	96.4	5.7	
6	22/09/88	15.0	T	101	12	8	8	28	49	96.1	36.4	29.3
			C	70	0	2	5	7	63	96.1	10.0	
10	29/09/88	12.0	T	77	0	19	13	32	13	97.0	71.1	15.0
			C	54	0	12	33	35	18	97.9	66.0	
16	04/10/88	12.0	T	99	3	7	3	13	35	96.8	27.1	12.5
			C	99	3	0	9	12	60	95.9	16.7	

Overall Mean Estimated Mortality From Turbine Effects 16.4

[1] T= Test, C = Control
[2] Injured = Whole Dead Fish With Visible Injury
Uninjured = Whole Dead Fish With No Visible Injury
[3] Mean Length of Recaptured Fish
[4] Uncorrected % Mortality = (Total Dead/# Captured) x 100
[5] Mortality From Turbine Effects

Table 2. Summary of 1988 alewife tests (Protocol 3).

Test	Date	Water Temp (°C)	Type[1]	Number Released	Number Severed	Whole Dead[2] Injured	Whole Dead[2] Uninjured	Total Dead	Total Live	Mean[3] Length (mm)	Uncorrected[4] Mortality (%)	Estimated[5] Mortality (%)
11	29/09/88	12.0	T	101	8	17	29	54	41	95.0	56.8	33.1
			C	98	1	15	18	34	56	95.2	37.8	
19	05/10/88	12.0	T	98	6	6	15	27	29	96.7	48.2	40.6
			C	98	0	0	11	11	75	95.5	12.8	
20	06/10/88	12.0	T	104	11	10	22	43	46	96.3	48.3	33.7
			C	100	0	1	21	22	78	95.7	22.0	
21	06/10/88	10.5	T	102	14	4	14	32	37	97.2	46.4	38.2
			C	100	1	1	6	8	52	97.0	13.3	
23	11/10/88	10.0	T	104	5	9	18	32	9	98.1	78.0	49.1
			C	101	0	7	14	21	16	100.3	56.8	

Overall Mean Estimated Mortality From Turbine Effects 38.9

[1] T= Test, C = Control
[2] Injured = Whole Dead Fish With Visible Injury
Uninjured = Whole Dead Fish With No Visible Injury
[3] Mean Length of Recaptured Fish
[4] Uncorrected % Mortality = (Total Dead/# Captured) x 100
[5] Mortality From Turbine Effects

Table 3. Summary of 1988 entrained alewife observations (Protocol 1).

Observation	Date	Water Temp (°C)	Number Severed	Whole Dead[1] Injured	Whole Dead[1] Uninjured	Total Dead	Total Live	Mean[2] Length (mm)	Total Captured	Estimated[3] Mortality (%)
1	19/09/88	16.0	4	6	2	12	33	94.8	45	26.7
2	11/10/88	11.0	6	10	7	23	116	76.6	139	16.5
3	12/10/88	10.5	14	21	49	84	125	76.4	209	40.2
4	12/10/88	10.5	11	27	48	86	273	73.0	359	24.0
5	13/10/88	10.5	49	34	66	149	100	91.2	249	59.8
6	18/10/88	10.5	164	-	-	1,468	1,210	-	2,678	54.8
7	18/10/88	10.5	40	-	-	164	218	-	382	42.9
8	21/10/88	10.0	4	28	51	83	85	97.3	168	49.4
9	21/10/88	10.0	2	6	16	24	36	92.9	60	40.0
10	25/10/88	9.5	3	11	6	20	12	87.4	32	62.5
11	25/10/88	9.0	8	10	23	41	63	97.2	104	39.4

Overall Mean Estimated Mortality 41.5

[1] Injured = Whole Dead Fish With Visible Injury
Uninjured = Whole Dead Fish With No Visible Injury
[2] Mean Length of Captured Fish
[3] Uncorrected % Mortality = (Total Dead/# Captured) x 100

Table 4. Summary of 1989 entrained alewife observations (Protocol 1).

Observation	Date	Water Temp (°C)	Number Severed	Whole Dead[1] Injured	Whole Dead[1] Uninjured	Total Dead	Total Live	Mean[2] Length (mm)	Total Captured	Estimated[3] Mortality (%)
1	28/09/89	15.0	104	-	-	390	1344	97	1734	22.5
2	28/09/89	15.0	96	-	-	441	1589	97	2030	21.7
3	29/09/89	15.0	53	35	29	117	412	100	529	22.1
4	29/09/89	15.0	97	-	-	190	1174	-	1364	13.9
5	29/09/89	15.0	49	-	-	102	1394	-	1496	6.8
6	29/09/89	15.0	22	-	-	30	367	-	397	7.6
7	02/10/89	14.0	7	2	3	12	40	96	52	23.1
8	04/10/89	13.0	57	58	66	181	878	97	1059	17.1
9	04/10/89	13.0	5	9	8	22	116	99	138	15.9
10	04/10/89	13.0	3	7	4	14	43	93	57	24.6
11	05/10/89	12.5	16	16	13	45	177	100	222	20.3
12	05/10/89	12.5	6	6	10	22	133	100	155	14.2

Overall Mean Estimated Mortality 17.5

[1] Injured = Whole Dead Fish With Visible Injury
Uninjured = Whole Dead Fish With No Visible Injury
[2] Mean Length of Captured Fish
[3] Uncorrected % Mortality = (Total Dead/# Captured) x 100

Table 5. Summary of 1987 - 1988 alewife tests.

Group	Number of Tests	Date of Data Collection	Water Temp Range (°C)	Type	Mean Severed	Mean Injured (%)	Mean Uninjured (%)	Dead Mean Length (mm)	Live Mean Length (mm)	Mean Mortality (%)	Mean Estimated Mortality (%)
'87 Transported Alewives (Ruggles and Palmeter 1989) (Protocol 4)	5	03/09/87 to 14/10/87	16.5 to 11.0	T	7.9 s = 5.2	23.8 s = 16.3	34.2 s = 19.1	82.7 s = 14.0	85.2 s = 15.8	78.9 s = 8.4	66.5 s = 12.7
				C	0	7.3 s = 4.6	19.6 s = 2.6	84.0 s = 14.3	86.1 s = 15.5	37.3 s = 5.3	-
'88 Stressed Alewives (Protocol 3)	5	29/09/88 to 11/10/88	15.0 to 10.0	T	9.4 s = 3.8	7.2 s = 2.2	15.1 s = 4.9	95.6 s = 1.7	97.8 s = 1.6	55.5 s = 13.2	38.9 s = 12.7
				C	0.2 s = 0.4	2.4 s = 2.7	11.8 s = 6.0	95.2 s = 2.5	97.6 s = 2.7	28.5 s = 18.8	-
'88 Unstressed Alewives (Protocol 2)	7	19/09/88 to 04/10/88	16.5 to 12.0	T	5.4 s = 3.3	10.9 s = 7.4	8.7 s = 10.3	94.5 s = 1.3	96.7 s = 1.8	34.4 s = 20.9	17.0 s = 7.7
				C	0.6 s = 1.1	7.3 s = 8.3	11.6 s = 15.0	95.4 s = 1.3	97.1 s = 1.2	21.8 s = 22.4	-

(s = standard deviation)

Table 6. Summary for 1987 - 1988 entrained alewife observations.

Group	Number of Observations	Date of Data Collection	Water Temp Range (°C)	Total Captured	Mean Severed (%)	Mean Injured (%)	Mean Uninjured (%)	Dead Mean Length (mm)	Live Mean Length (mm)	Estimated Mortality (%)
1987 (Ruggles and Palmeter 1989) (Protocol 4)	10	15/09/87 to 14/10/87	17.5 to 11.0	11,955	7.9 s = 3.3	–	–	91.4 s = 3.1	–	14.0 s = 3.6
1988 (Protocol 1)	11	19/09/88 to 25/10/88	16.0 to 9.0	4,425	7.9 s = 5.0	13.6 s = 8.4	19.0 s = 9.4	82.7 s = 11.5	90.5 s = 9.6	41.5 s = 14.8
1989 (Protocol 1)	12	28/09/89 to 04/10/89	15.0 to 12.5	9,233	6.7 s = 4.1	15.0 s = 9.8	16.2 s = 11.7	96.1 s = 2.1	98.4 s = 2.5	17.8 s = 6.4

(s = standard deviation)

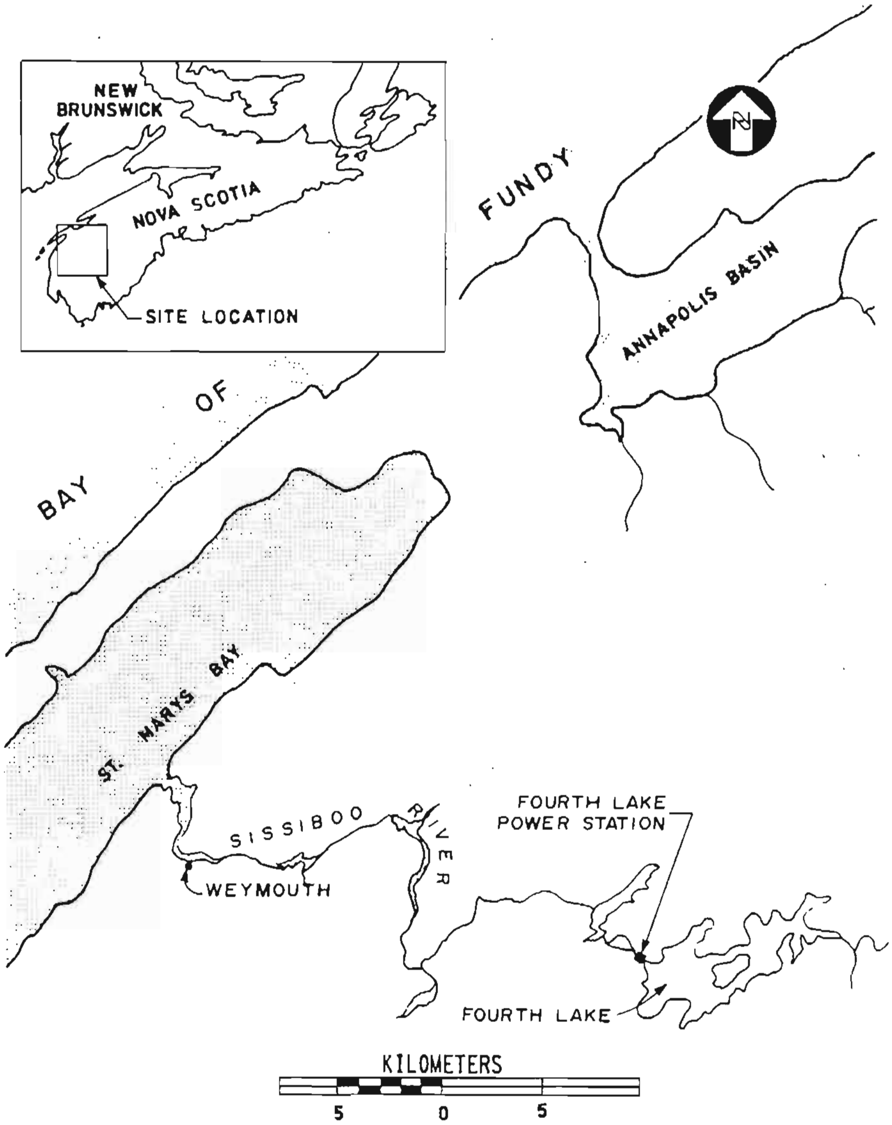

Figure 1. Site location.

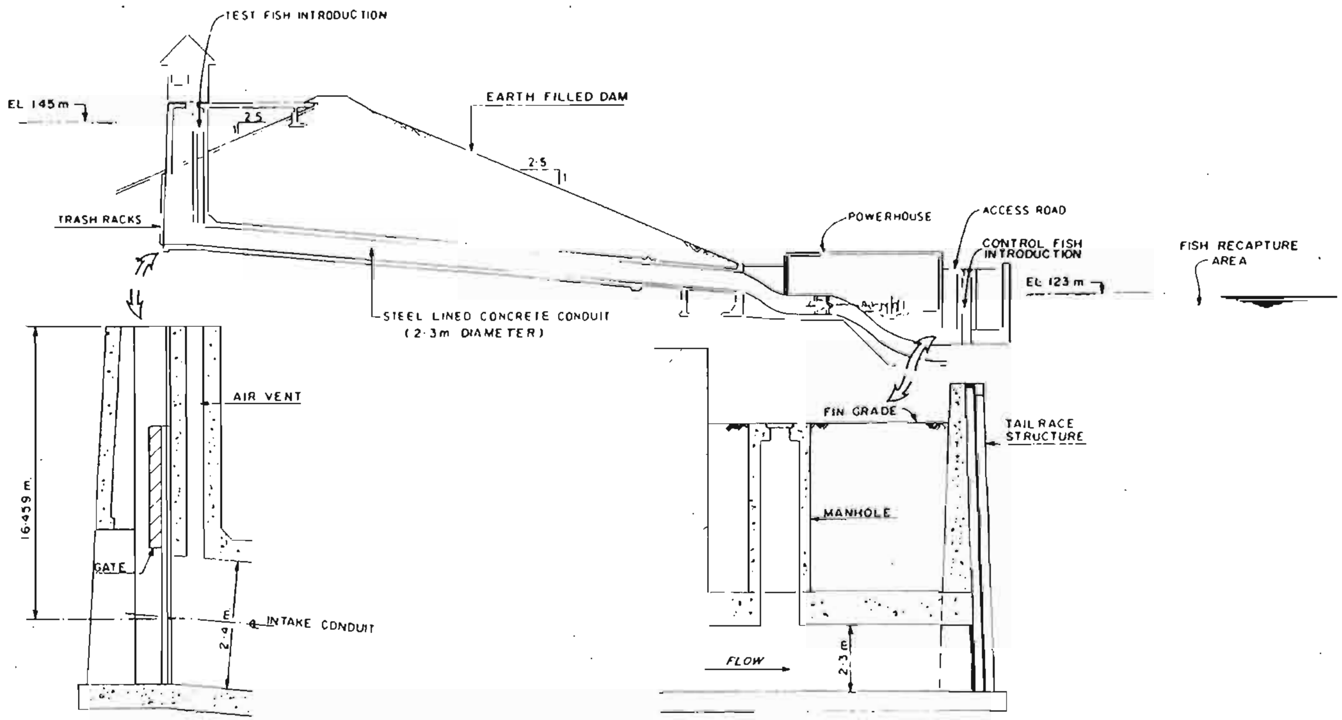

Figure 2. Layout of the Fourth Lake power station showing locations of fish introduction and recovery.

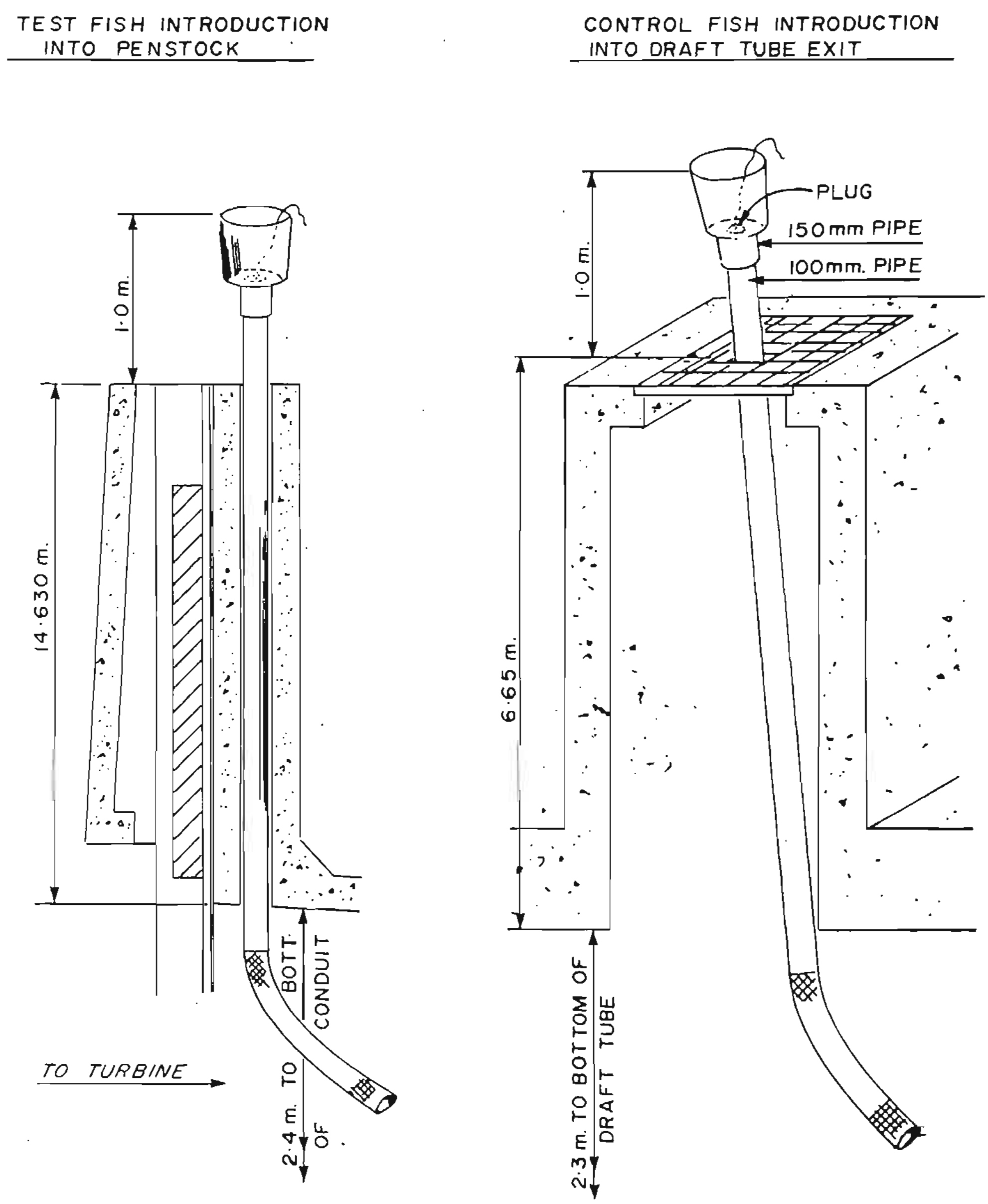

Figure 3. Fish introduction apparatus.

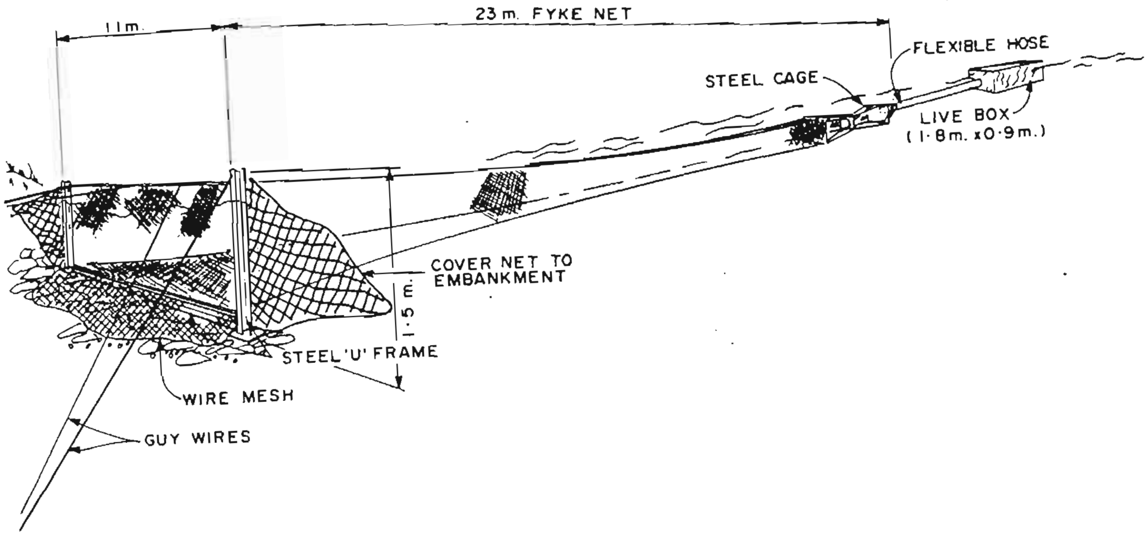

Figure 4. Fish recovery apparatus.

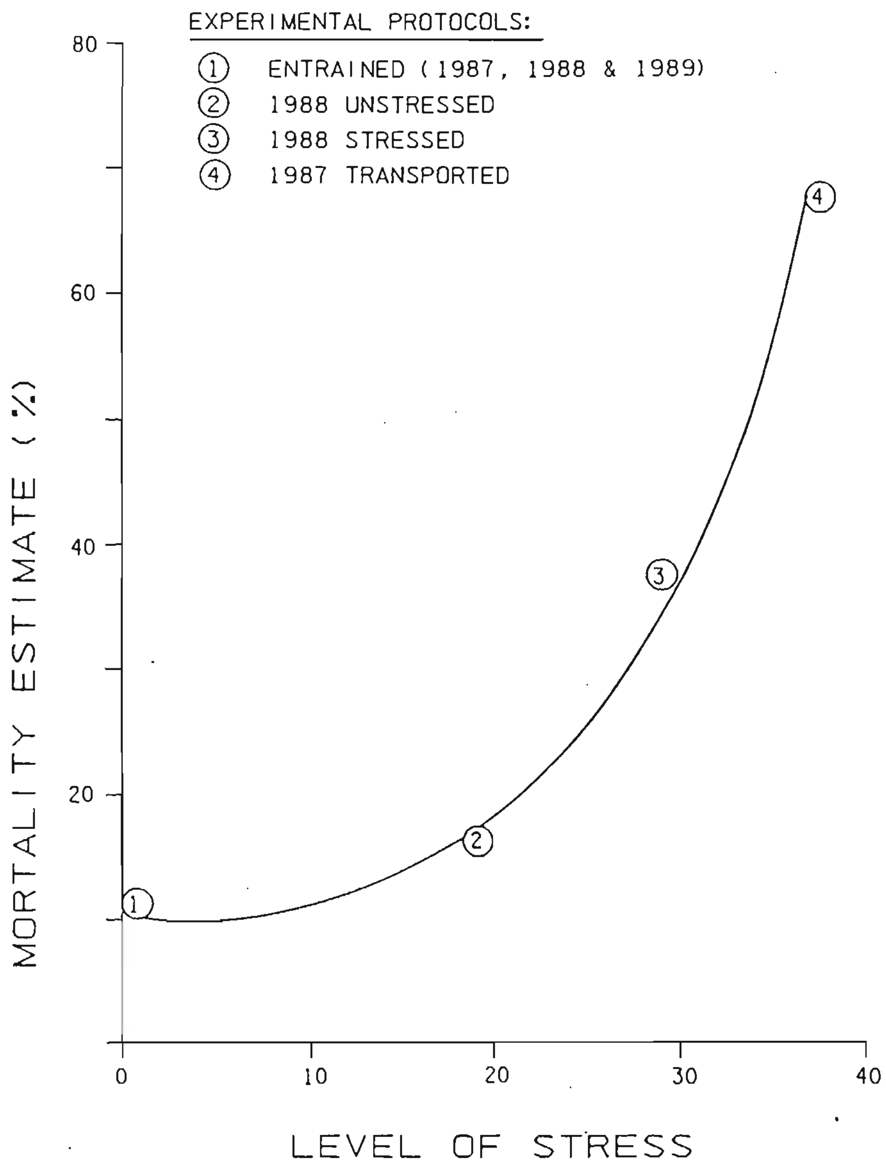

Figure 5. Effect of stress imposed by four experimental protocols on turbine fish passage mortality estimates. The mean control mortality for each protocol was used as a measure of stress.

RELATIVE SURVIVAL OF JUVENILE CHINOOK SALMON (*Oncorhynchus tshawytscha*) THROUGH A BONNEVILLE DAM ON THE COLUMBIA RIVER

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ABSTRACT

Juvenile chinook salmon that passed through the Bonneville second powerhouse juvenile bypass system, during the summer, had significantly lower survival rates than upper and lower turbine, spillway, and downstream control groups. Predation by northern squawfish (*Ptychocheilus oregonensis*) was suspected to have been the cause of high mortalities among bypassed fish. No significant differences existed between survival rates of upper and lower turbine groups. Estimates of long term survival using adult returns are incomplete at this time.

INTRODUCTION

Bonneville Dam is at km 235 on the Columbia River, approximately 65 km east of Portland, Oregon (Figure 1). The first powerhouse was completed in 1938, while the second was added in 1983 to provide additional peaking capacity. A navigation lock, spillway, adult and juvenile fish passage facilities at each powerhouse, the Bonneville Fish Hatchery (salmon rearing facility), and visitor facilities are present at the dam. These features were designed and built by the Corps of Engineers (COE), Portland District, North Pacific Division.

COE has designed and constructed adult salmon passage facilities into each of the eight dams on the Columbia River mainstem. COE has also funded an extensive program to retrofit four of these powerhouses with juvenile bypass systems to allow downstream juvenile Pacific salmon (*Oncorhynchus* spp) migrations. In addition, juvenile salmon passage facilities were included in the original design of the two most recent powerhouses, Lower Granite Dam and the Bonneville second powerhouse. The Bonneville second powerhouse juvenile fishway design incorporates knowledge gained from 20 years of research funded by COE.

The Bonneville second powerhouse juvenile bypass system has one 6.1 m submersible travelling screen (STS) in each intake of all eight turbines, for a total of 24 screens. These screens set up a hydraulic cushion that deflects juvenile salmon away from the turbine intakes and into vertical bulkhead slots. Once in the vertical slots, the fish exit by their own volition through 30 cm orifices into a collection gallery that travels the length of the powerhouse to a dewatering station. At this station, a subsample of the fish population is taken for the purpose of monitoring the migration. Much of the water is removed through an inclined dewatering screen, while the remaining 61.0 m^3/s travels down a buried 91 cm diameter pipe at 46 to 74 cm/s and discharges through an underwater outlet structure into the tailrace. The outlet is mid stream, approximately 6.1 to 14.6 m under the tailrace surface, and in an ambient water flow of 1.0 m^3/s. The outlet had these features because previous research (Fahler 1988; Poe and Reiman 1988) suggested that they may reduce predation by northern squawfish (*Ptychocheilus oregonensis*).

In 1983, COE funded the National Marine Fisheries Service (NMFS) to conduct a routine evaluation of the bypass system to ensure the system was functioning properly. This included monitoring the condition of fish being bypassed as well as the efficiency with which the STS's were guiding fish away from the turbines.

Since 1983, NMFS research has shown that STS guidance efficiency was poor for all species. A guidance efficiency of 70% during spring and 50%

during summer migrations is acceptable according to regional fisheries agencies and Indian Tribes. Summer guidance efficiency for subyearling chinook was only 24% at the Bonneville second powerhouse. Three test modifications allowed spring migration guidance efficiency to increase from 19 to 67%. These modifications were: i) a turbine intake extension (TIE) was developed and placed on the forebay face of the dam. The TIE reconfigured the shape of the intake to produce smoother hydraulic conditions leading into the units; ii) the STS was lowered 73.5 cm to intercept more intake flow, and thus more juveniles; and iii) the standard trashracks were replaced with streamlined trashracks. These used crossmembers which were angled to the appropriate flow for each elevation or section of the trashrack based on hydraulic model studies. The streamlined trashracks provided improved flow alignment, reduced turbulence downstream of the trashrack, and thus improved guidance into the bypass system. These changes however did not improve the guidance of summer migrants beyond the original 24%.

Poor subyearling chinook guidance resulted in most of the juveniles being passed through the turbines when the powerhouse was operated during the summer. These fish did not respond to any bypass improvements and our knowledge regarding the survival rates of these fish through various passage routes at Bonneville Dam was limited. Therefore, further information was needed to make operational decisions that would afford protection for subyearling salmon.

The Corps of Engineers funded NMFS to conduct a multiple year evaluation of the comparative survival of subyearling chinook salmon through various passage modes (turbines, spillway and bypass) at the dam. The study was designed to examine both juvenile and adult data. Using this information, operational scenarios could then be formulated to provide additional juvenile protection while meeting power system demands.

METHODS

The evaluation was designed to estimate short and long term survival rates. Short term relative survival was based on recoveries of marked fish just above the Columbia River estuary and approximately 157 km downstream from Bonneville Dam, while long term survival will be based on returns of coded wire tagged adult fish.

The estuarine sampling of marked juveniles provided information on the success of various release strategies by comparing recovery percentages. These short term recoveries provided immediate survival information and ensured that the release sites did not introduce biases.

Between 1987 and 1990, approximately 2.2 million subyearling upriver bright fall chinook salmon were reared annually (100-165 fish/kg, 83 to 99 mm) at the Bonneville Fish Hatchery. Special measures were taken to ensure that test fish did not differ in size, condition or rearing history. Each treatment group was marked by a unique coded-wire tag, with cold brands used to identify recovered fish from the various treatment groups.

Six release sites were tested:

1. upper turbine
2. lower turbine
3. bypass system
4. turbine frontroll*
5. spillway
6. downstream (midriver).

* frontroll is the downstream side of the upwelling turbine boil.

The downstream site was located approximately 2.5 km downstream from the dam (Figure 2). The site was assumed to be downstream from the effects of the dam and was located mid-river to be away from the effects of shoreline oriented predators such as northern squawfish.

During the tests, turbines were operated at maximum efficiency for the available hydraulic head and prevailing river conditions. Second powerhouse units were selected and operated to provide good flows downstream from the project. Test units were operated for 2 to 3 hours prior to each release and for approximately 6 hours after each release. Releases were made at approximately 0200 hours to minimize predation and to coincide with normal periods of passage. Each night, fish were released at each test site such that they entered the tailrace at approximately the same time.

Beach seines and mid river purse seines

were used to recover marked juveniles near the upper end of the estuary (Figure 1). Sampling was conducted for 8 to 16 hours per day, 7 days a week. Each year, periodic diel purse seine sampling was conducted. Captured fish were examined for brands, excised adipose fins, descaling, injury, and fork length.

Percent recovery differences were evaluated (Ledgerwood *et al.* 1990) by analysis of variance (ANOVA) using a randomized block design in which each release day was considered a block (Sokal and Rohlf 1981). Among group percent differences in descaling were also evaluated using ANOVA. Fisher's protected least significance procedures were used to rank treatment means for significant F-tests (Peterson 1985). Chi-square goodness of fit was used to test the hypothesis that different marked groups, released on the same day, had equal probability of capture through time (Zar 1974). Chi-square was also used to test whether treatment groups had equal probability of capture during darkness.

RESULTS

SHORT TERM SURVIVAL

Juvenile recoveries at the upper end of the estuary ranged from 0.44% to 0.96% between 1987 and 1990. These recoveries are, for the most, part within the design criteria of 0.5% recovery percentage. Handling mortality of recovered fish was less than 0.5% and there was no significant difference between the descaling rates among treatment groups. In general, there was no significant difference between the timing of treatment group movements (Ledgerwood *et al.* 1990).

According to Ledgerwood *et al.* (1991) there were significant differences ($\alpha = 0.05$) in mean recovery percentages among various treatment groups. Between 1987 and 1990, the lowest percent recoveries were from bypass, followed in ascending order by lower turbine, upper turbine, frontroll, downstream, and spillway. Not all treatments were tested each year (Table l).

During the first two years of the study (1987 and 1988), the percentage of bypassed fish that were recovered was significantly lower than the percentage recovered after turbine passage. The mean differences were 10.9% in 1987 and 13.6% in 1988. These data suggest that passage through the bypass system was detrimental to the survival of the juvenile salmon. In 1989 and 1990, the percentage recoveries of bypassed fish were not significantly lower than recoveries of turbine passed fish. The mean differences were 3.2% in 1989 and 2.5% in 1990. The combined data for all four years indicate a significant difference (6.8%), between the lower turbine release and the bypass release groups (Ledgerwood *et al.* 1991).

For each year of the study, the percentage recoveries of fish from upper turbine release sites were almost identical with those from lower turbine release sites (Table 1).

Comparisons of percent recoveries can also be made among the bypass and non-turbine treatments (Table 1). These comparisons are based on less than four years of recovery data. The 1988 to 1990 data show that bypass groups were recovered at rates from 3.6% to 14.1% lower than the tailrace groups released into the frontroll of the turbine. Respectively, the 1988 and 1989 bypass recoveries were 23.1% and 11.6% lower than the downstream groups. The 1989 bypass recoveries were 16.6% lower than the spillway groups.

LONG TERM SURVIVAL

Recoveries of adults from the 1987 juvenile releases indicate that no significant difference between the long term survival of bypassed and turbine passed fish. Approximately 1.9% more bypassed fish were recovered than turbine passed fish. There have been insufficient adult recoveries to date from the 1988 - 1990 releases for analysis (Ledgerwood *et al. 1991*).

DISCUSSION

The fact that bypass recoveries were usually lower than recoveries from other treatment groups suggests bypass passage may have been detrimental to juvenile salmon survival. However, decreased survival may have been due to predators (northern squawfish) keying on the single point outfall of the juvenile bypass system which functions as a source of concentrated prey. Preliminary results also showed that the Bonneville second powerhouse turbines provided better passage conditions and higher rates of survival than were assumed under test conditions.

The fundamental assumption that bypasses provide a better passage route than turbines should be examined at other powerhouses. Unfortunately, bypass evaluations at other mainstem hydroelectric projects have been limited to assessing survival at a collection point within the bypass system, and not below the tailrace. The fact that previous studies suggest very low injury and mortality rates confirms that proper engineering criteria were used to design the bypass system components (gatewells, orifices, collection galleries, dewatering screens, and transportation channels). The present study is the only one known by the author that investigates survival of bypassed fish beyond the point of discharge.

Researchers on the Columbia River noted large populations of northern squawfish around the mainstem dams and suspected that predation may be a significant problem. The first large scale evaluation of predator abundance and consumption rates in a major reservoir was conducted in the pool behind John Day Dam by the U.S. Fish and Wildlife Service and the Oregon Department of Fish and Wildlife between 1983 and 1986 (Poe and Reiman 1988). They estimated that 1.9 to 3.3 million juvenile salmonids were consumed annually, which represented from 9 to 19% of the estimated number of juveniles that entered the John Day pool. They concluded that "direct removal of northern squawfish may be a feasible measure for reducing predation on juvenile salmonids in reservoirs."

Predator indexing studies are ongoing in other reservoirs of the Columbia River to assess the system-wide impact of predators on juvenile salmon populations. These studies are being conducted concurrently with predator removal research to determine the best removal method(s), markets, and whether the fishery is sustainable (biologically and economically).

The Bonneville second powerhouse survival data suggest that predator control programs associated with predator indexing investigations should be expanded. However, even if older age classes of predators are eliminated (20% removal of northern squawfish), predation would only be reduced by up to 50%. A significant threat to migrating smolts would remain.

The Bonneville second powerhouse was designed and constructed with a "state-of-the-art" juvenile bypass system. However, in view of the present study, the juvenile bypass system outfall requires further examination. The Bonneville survival data suggest that a 1 m^3/s ambient flow past the outfall, and placement of the outfall away from the shoreline, at mid-depth, do not eliminate all predator-prey encounters. Unfortunately, this study was not designed to determine whether predation is the main cause of mortality among bypassed fish. Studies are currently underway to examine whether apparent mortality is a result of the bypass itself or predation.

CONCLUSIONS

According to Ledgerwood (1990), the juvenile and adult chinook data indicate the following:

1. Fish released into the juvenile bypass system had significantly lower rates of survival than other passage routes.

2. Differences in survival between the upper and lower turbine treatments were not significant.

3. Fish released into the spillway (1989 only) had significantly higher mean recovery percentages than bypass and turbine treatment groups.

4. NMFS speculates that predation by northern squawfish is a major cause of mortality among bypassed fish.

RECOMMENDATIONS

a) Project operators who have installed, or are considering installing juvenile systems should evaluate their effectiveness to ensure that survival has improved. Factors including predation at the outfall may substantially influence the success of the bypass system.

b) Assumptions that are critical to the success of any mitigation program should be thoroughly researched to ensure that project objectives are met.

c) Current juvenile bypass system outfall design criteria need to be further evaluated to provide maximum salmonid protection.

d) Predator control efforts on the Columbia River should be expanded.

e) Additional studies should be conducted to evaluate the survival of spring migrants that pass through the Bonneville second powerhouse bypass system.

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Table 1. Summary of juvenile recovery percentages and percentage differences among groups, Bonneville Dam survival study, 1987-1990.

Treatment	1987	1988	1989	1990 [a]
Recovery Percentages				
Bypass	0.5764	0.4376	0.8007	0.5577 (10 groups) [b]
Bypass				0.5106 (21 groups) [b]
Upper Turbine	0.6402	0.5024	0.8298	nt [c]
Lower Turbine	0.6528	0.5104	0.8256	0.5721 (10 groups) [b]
Tailrace	nt	0.5095	0.8637	0.5686 (10 groups) [b]
Tailrace				0.5299 (21 groups) [b]
Downstream	0.5567 [d]	0.5690	0.9061	nt
Spillway	nt		0.9604	nt
Percentage difference from bypass [d]				
Turbine [f]	+10.9 *	+13.6 *	+3.3	+2.5 (10 groups)
Turbine	nt	+14.1 *	+7.3	+3.6 (21 groups)
Downstream	[d]	+23.1 *	+11.6 *	nt
Spillway	nt	nt	+16.6 *	nt

a Data from 1990 are considered preliminary until appropriate review.

b In 1990, the first 11 turbine release groups were compromised, thus only the last 10 groups can be compared to bypass or tailrace release groups. All 21 groups can be used for comparing the bypass to tailrace release groups.

c nt = not tested.

d The downstream release in 1987 was made at the shoreline. Subsequently, lower recovery percentages of that treatment led to an *a posteriori* decision not to use these data for assessing relative survival of the treatments released in mid-river.

e Calculated using annual means for recovery percentage of bypass groups (BY) = [(treatment% - BY%) ÷ treatment%] x 100.

f Average of upper and lower turbine percentages.

* Indicates significant differences at $\alpha = 0.05$.

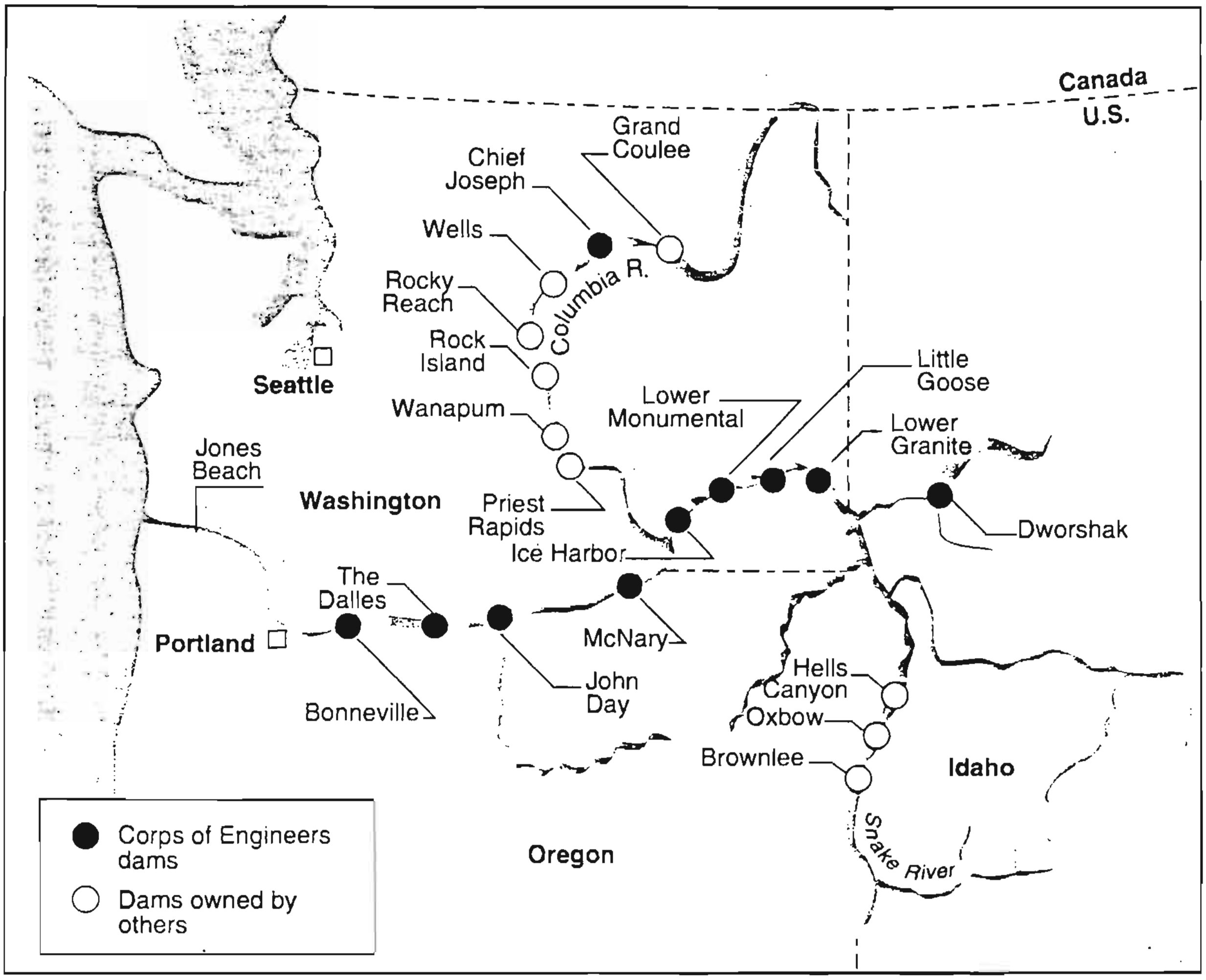

Figure 1. The Columbia River showing the location of the Bonneville Dam and the Jones Beach recovery site.

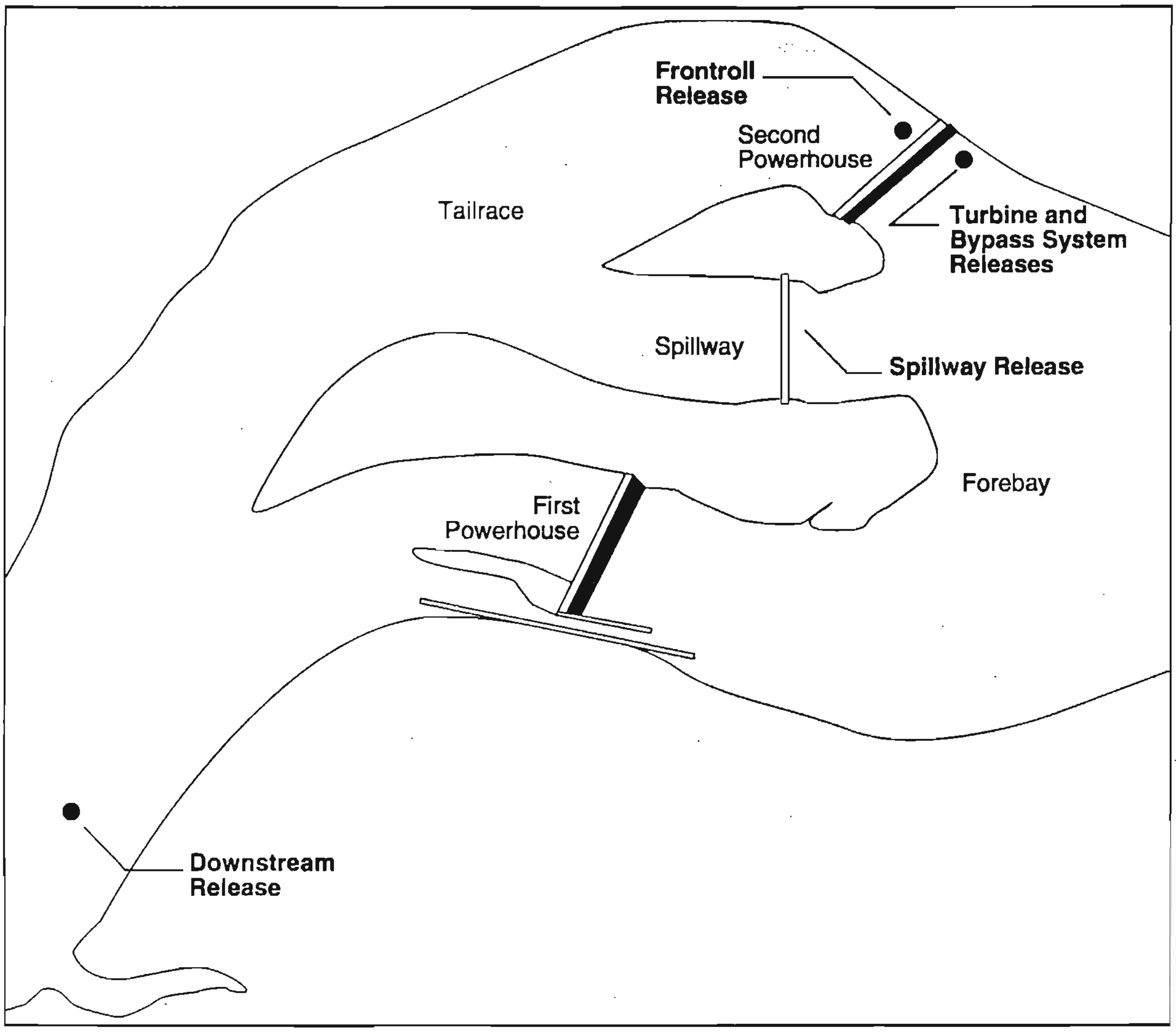

Figure 2. Bonneville survival study release locations.

MITIGATION TECHNOLOGY AT HYDROELECTRIC DAMS

UPSTREAM ATLANTIC SALMON (*Salmo salar*) PASSAGE

by

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ABSTRACT

Upstream salmon passage through a dam is broken into three components: the fishway entrance, the fishway and the exit. Design considerations and alternative types of components are presented.

INTRODUCTION

The problem of upstream fish passage through a dam or other obstructions can be divided into three parts: the fishway entrance, the fishway (or other means of transport), and the exit. Entrance considerations are the same for all species and for all means of fish transport. Fishway size and configuration (or size and type of other means of transport) depend upon the species, maximum number of fish to be transported per day, reservoir levels during the run and height of dam to be surmounted, etc. Exit considerations are related to fluctuation of reservoir levels and location with relation to spillway and turbine intakes.

These three components are considered below:

FISHWAY ENTRANCES

Entrances should be positioned as far upstream as the fish can swim with respect to obstacles. Pitlochry Dam and Fishway on the River Tummel, Scotland, (Figure 1) is a good example. The entrance is constructed where the fish naturally congregate, at the apex of a triangle formed by the river bank and a screened tailrace. Other examples are presented in Clay (1961, 1992) and various other publications. They describe dam, powerhouse and spillway designs using diverse spill and outflow conditions (i.e., gated spills leading to the fish entrance, the elimination of back eddies near the banks of the river, and powerhouse collection systems).

Auxiliary water must be available to a powerhouse collection system because water velocities of 1 to 2 m/s must flow through each of the multiple entrances. Auxiliary flows are also desirable at fishway entrances to maintain velocities between 1 and 2 m/sec.

When a powerhouse makes use of water diverted from a river, the home stream odor may be insufficient to lead fish past the powerhouse. This problem may be overcome by increasing the flow until the home stream odor is sufficient to attract fish. The Seton Creek Project in B.C. (Fretwell 1989) is an example of increased natural stream flow. Alternatively, one may install a device to exclude fish from the tailrace. A simple barred screen (i.e. at Pitlochry), or a more elaborate barrier dam or electrical barrier may be used to exclude fish from the tailrace. The best solution may be a graduated electrical barrier similar to one manufactured by Smith Root Electronics.

FISHWAYS OR OTHER FORMS OF TRANSPORT

Swimming ability should be the first consideration in fishway design. Atlantic salmon are among the best swimmers of all the salmonid species studied thus far. Beach (1984) noted that water temperature and fish size are probably the only factors that will affect their swimming speed. The endurance of salmon swimming at maximum speed may be reduced from 10 minutes to 30 seconds by increasing the temperature from 10 to 25°C. Also the maximum swimming speed of a fish 50 cm in length is considerably less than a fish of 100 cm.

Fishways with 50 cm drops per pool would be satisfactory, at dams, providing there were no extreme temperatures at the time of migration. This limit takes into account the smallest smolts that are likely to be migrating. Fishways with a large drop per pool such as 60 cm have been used but are not recommended for installation at a dam or series of dams such as those under consideration.

Pool and weir fishways have been used in Atlantic salmon passage for a century or more. The minimum recommended size for pool and notched weir fishways is 1.6 m wide, 2 m long and 1.6 m deep. Use of either a submerged orifice, or an overflow weir combined with a submerged orifice, increases flow in the fishway causing a build up of energy. Larger pools may be used to dissipate this built up energy. Water surges may be a problem at long weir type fishways that have more than 75 baffles.

The problem of headwater fluctuation is overcome through careful fishway selection. Automatic telescopic weirs or folding weirs may be built above the reservoir to control water flow in the fishway if headwater fluctuations (eg. pool and weir fishways) are a problem. These adaptations are successful but can greatly increase construction costs, depending upon the extent of fluctuation.

Vertical slot baffles may be constructed in short fishways, to overcome headwater fluctuations. Denil fishways also overcome headwater fluctuation problems but do not provide as much flexibility. Larinier's (1983) guide recommends an overall width of 0.8 m and a slope of 20% for Denil fishways. He provides other combinations of dimensions but they are less acceptable for Atlantic salmon.

Fish locks, hoists and elevators are other means of transport. Fish locks are available in many designs. The Borland Lock is frequently used in upstream Atlantic salmon passage. Locks are relatively economical to construct and, because of their limited capacity, are useful for the small runs usually encountered in Atlantic salmon streams.

Fish elevators or hoists are more economical in terms of water usage and construction cost. Construction costs are independent of dam height. This mode however, requires fish handling which may lead to injuries and disorientation of fish. Elevators and hoists have been used with some success in the Maritime provinces. Two alternate methods include the use of a collection system leading to a bucket conveyor which empties into the reservoir above the dam, or collection followed by truck transportation.

Table 1 summarizes the alternatives for upstream Atlantic salmon passage.

FISH EXITS

When deciding upon the location for a fishway exit, one must consider whether the fishway will be used only for upstream migrations, or if smolts and kelts will also be using the facility for downstream passage. If it is to be used for upstream runs only, the exit should be positioned as far as possible from the spillway or powerhouse intakes to prevent adult fish from being swept downstream. However, if the adult exit is also to be used as an entrance for outmigrating fish then it must be placed close to the turbine intakes. The surface outflow will act as an attractant for these fish. Obviously, compromises must be made when smolts and adults use the same fishway.

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Table 1. A summary of alternatives for upstream Atlantic salmon passage.

Type	Advantages	Disadvantages
Pool & Notched Weir	minimum pool size	problem of headwater fluctuation
Pool with Submerged Orifice	some flexibility with headwater changes	larger pool size
Combination of Above	same flexibility with headwater	larger pool size
Vertical Slot	solves problem of headwater fluctuation	never been used for long fishways
Denil	limited headwater fluctuation	unproven for long fishways
Fish Lock	more economical for high dams	limited headwater fluctuation
Fish Elevator:		
1. Bucket Conveyor	no headwater problem	some handling of fish
2. Trucking Operation	no headwater problem	more handling of fish

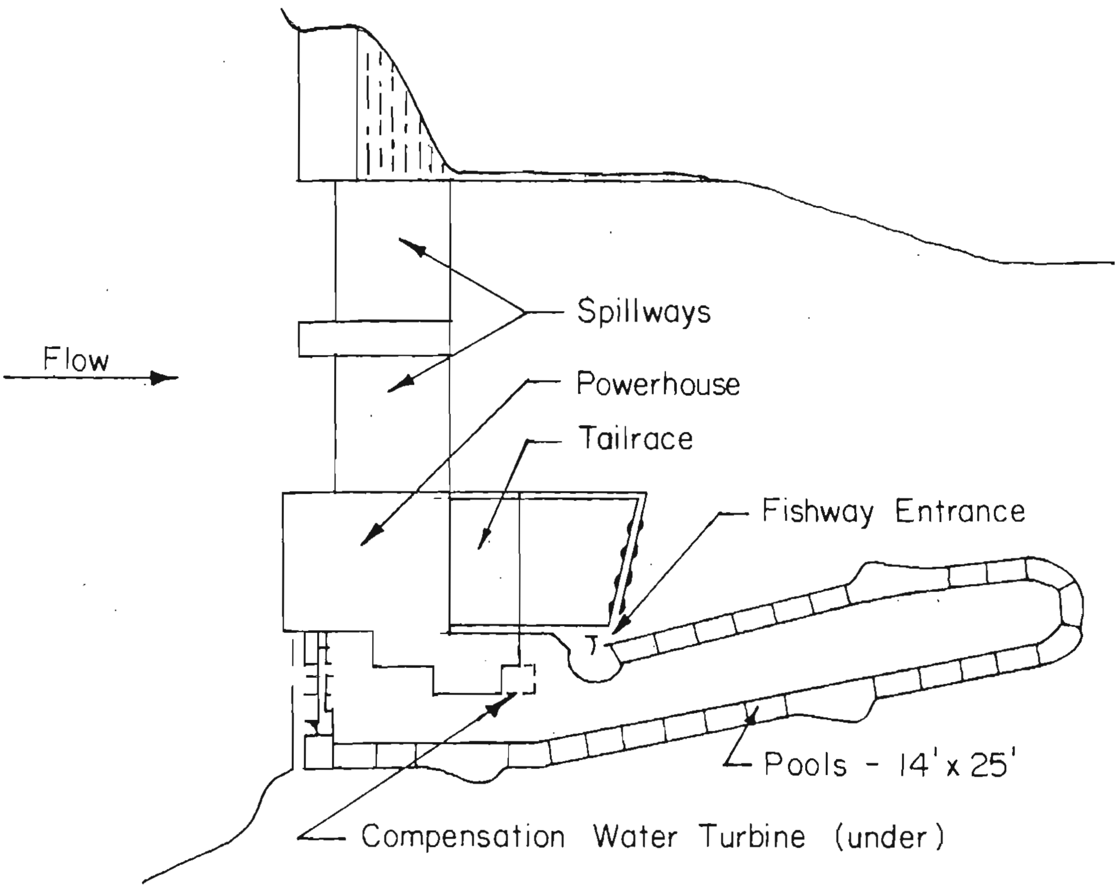

Figure 1. Pitlochry Dam.

AN UPDATE OF METHODS FOR PREVENTING TURBINE MORTALITY AT HYDRO PROJECTS

by

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ABSTRACT

Behaviourial and physical barriers as well as various collection and diversion systems are presented as methods used to prevent turbine passage of fish at hydroelectric developments. Sound projectors, strobe lights and mercury lights are presented as repellents/attractants that may be used in hybrid barriers and should be investigated further. Physical barriers such as barrier nets, bar racks and fixed screens have been used successfully over a wide geographic range with various fish species, physical layouts and hydraulic conditions. Fish pumps and travelling screens (collection systems), angled screens, angled rotary drum screens, the Eicher screen and louvers (diversion systems) are presented as alternatives that would be viable under specific conditions.

INTRODUCTION

The passage of fish through hydraulic turbines and the potential for injury and mortality have long been a concern in the hydroelectric industry. In the 1950's and 1960's, much of the research effort into fish passage was directed toward quantifying the degree to which injury and mortality were occurring at many North American hydro projects. Due to the high variability in results, research since the 1970's has concentrated on developing methods for preventing fish passage through turbines. Investigations have been conducted into a variety of physical and behaviourial forms of mitigation. Despite years of research and development, there are few technologies that meet the 100% success criteria imposed by resource agencies, are practical to construct and operate, and are cost effective. In cases where 100% effectiveness is not required, various technologies, or combinations of technologies, can be considered. This paper offers an overview of existing technologies, current research and the potential for successful application of each technology.

CURRENT STATUS OF FISH PROTECTION ALTERNATIVES

A detailed review of the biological effectiveness, engineering practicality, and costs of these systems and devices is presented in an Electric Power Research Institute report (EPRI 1986). The EPRI report was prepared by Stone & Webster Engineering Corporation and is currently being updated for publication in 1992. The following is a brief summary of the status of fish protection technologies available as of the end of 1991. Broad categories of devices and systems (ie., behaviourial barriers, physical barriers etc.) are presented in Table 1.

BEHAVIOURIAL BARRIERS

Electric Screens - Electrical barriers effectively prevent the upstream passage of fish, however, a number of attempts to divert or deter the downstream movement of fish have met with very limited success. Most applications are no longer in operation. Electrical barriers also pose a serious safety threat to humans. Given their past ineffectiveness and their hazard potential, electric screens are not considered a viable technology at this time.

Several electrical barrier manufacturers continue to claim that their products are effective in preventing downstream fish passage even though there are no supporting data (numerous attempts to obtain such data have been made) to confirm such claims.

Air Bubble Curtains - Air bubble curtains are ineffective in blocking or diverting fish. Very little data are available on the effect of air bubble curtains on salmonid movements. This form of technology is no longer in use.

Hanging Chain Barriers - Chain barriers have been partially successful under laboratory conditions. Unfortunately, field research has not been able to replicate these results, therefore, research into this form of technology has ended.

Strobe Light - Strobe lights effectively repel selected fish species in laboratory and field experiments. Between 1988 and 1991, strong repeated avoidance responses were elicited among juvenile American shad (*Alosa sapidissima*) outmigrants at the York Haven Hydro Project on the Susquehanna River in Pennsylvania (EPRI 1990; EPRI 1992). Even after hours of exposure, the fish did not become acclimated to the light. It was possible to periodically (once per hour) pulse the fish through an ice/trash sluiceway located adjacent to the downstream-most hydro unit (Figure 1), thereby preventing turbine passage. In 1991, netting was used in the sluiceway and the turbine discharge to quantify numbers of fish being passed. These results indicated that approximately 94% of the fish in the area of influence of the strobe lights passed through the sluicegate.

Avoidance has also been demonstrated among Atlantic (*Salmo salar*), chinook (*Onchorynchus tshawytscha*) and coho salmon (*O. kisutch*), and steelhead trout (*O. mykiss*) in laboratory experiments at the University of Washington (EPRI 1990). Georgia Pacific (1988, 1989, 1990) has had varying success when using strobe lights to repel Atlantic salmon smolts and kelts from a turbine intake at a hydro project in Maine. Further field studies are required to evaluate the success of this technology in terms of salmonid movements. Strobe light systems should be used in conjunction with other protection measures at sites with stringent success criteria (ie., 100 % effective). Given the excellent results obtained with American shad juveniles, it is likely that other species may be repelled by strobe lights and then bypassed at a high rate given proper system design, layout and operating conditions. Additional design development efforts at the York Haven Project are ongoing.

Mercury Light - Mercury light is an effective attractant under both laboratory and field conditions. Mercury lights were used in the Wapatox Canal on the Naches River in Washington (Figure 2) to significantly increase the passage of chinook salmon into a drum screen bypass (EPRI 1990).

Laboratory studies of mercury lights at the University of Washington showed inconsistent results (neither strong attraction nor avoidance) with Atlantic, chinook and coho salmon juveniles. Steelhead trout, on the other hand, showed a strong prolonged attraction to the mercury lights. Follow-up studies in the field have not been conducted with these species.

While responses to mercury light appear to be species-specific, this light source is considered to have good potential for protecting fish, particularly if used in conjunction with other devices or technologies (eg., spillways and diversion system bypasses). Additional field studies are required. Mercury lights are relatively inexpensive and can be evaluated easily.

Sound - Some species are attracted to sound generators (poppers, hammers, pulsers and projectors) while others are repelled or show no response. EPRI studies indicated that a mechanical sound generator known as a "hammer" did not significantly alter the behaviour of a number of fish species under both laboratory and field conditions. Studies by Nova Scotia Power showed inconsistent results when using sound devices.

Recently, scientists at the U.S. Army Corps of Engineers Waterways Experiment Station and the New York Power Authority independently evaluated similar underwater sound projectors which operated in the 120 to 150 kHz range. Both groups claim to have effectively repelled alewife (*Alosa pseudoharengus*) and blueback herring (*A. aestivalis*). Additional studies are ongoing.

Loeffelman *et al.* (1991) indicates 94 and 81% success respectively when repelling outmigrating steelhead trout (18 cm long) and chinook smolts (9 cm long) with low frequency sound (200 to 800 Hz) emitted by underwater sound projectors. The projectors were placed upstream of the power canal entrance to the Buchanan Hydroelectric Project on the St. Joseph River in Michigan.

These results are encouraging, however, sound generators have not been fully evaluated under normal conditions at hydro plants. Therefore, additional research is required to determine whether sound devices can be employed to effectively divert fish to a bypass.

Water Jet Curtain - This device has received only minor attention. While several small-scale studies indicate that several species avoid a water jet barrier, mechanical and reliability questions have prevented further study and field applications.

Chemicals - There have been very few studies in which chemicals were used as fish protection agents. Those that have been tested were not effective.

Hybrid Behaviourial Barriers - A number of studies have been conducted to determine whether various combinations of behaviourial devices can increase overall biological effectiveness. Field trials indicate that hybrid barriers are not usually effective. However, many of these field evaluations did not make use of anadromous species and were conducted at hydroelectric projects. Various combinations of biological barriers should be considered in the future.

PHYSICAL BARRIERS

Infiltration Intakes - Radial wells and artificial filter beds have been used successfully to supply small quantities of water. However, they have not been developed to screen large flow volumes or for water use systems such as power generating facilities, therefore, their applicability for fish protection is unknown.

Porous Dike - Experiments have shown that rock dikes can effectively allow water passage while repelling fish. Such dikes have not been used to filter large quantities of water.

Cylindrical Wedge-Wire Screens - These screens are generally used to prevent the passage of early life stages of fish into low-volume intake systems. A notable exception is Consumers Power's James H. Campbell Plant on Lake Michigan which receives 20 m^3/s via 28 fixed wedge-wire screens. While the system is relatively complex, it has operated well. Application to plants with higher flow rates would not be cost-effective.

Barrier Nets - Under the proper hydraulic conditions and without heavy debris loading, barrier nets have been very effective in blocking fish passage into intakes. Two recent studies demonstrated the effectiveness of barrier nets at two very different projects. At the Ludington Pumped Storage Plant on Lake Michigan, a 4 km long barrier net, set in open water around the intake jetties, has been successful in dramatically reducing fish entrainment (all species) during pumpback operations (J. Gulvas, Consumers Power Company, pers. comm.). Scientists at the Pine Hydro Project in Wisconsin conducted a two-year evaluation of a barrier net placed between the dam and the shoreline upstream of the plant's power canal intake (Figure 3). The net substantially reduced entrainment of all species and was operationally reliable throughout the study (Stone & Webster 1991). Barrier nets have not been tested as diversion devices for migratory species, however, such investigations are warranted on the basis of these results, and since the nets are relatively inexpensive.

Bar Racks - Bar rack avoidance by fish has been well-documented. The rack acts as a physical barrier to larger fish and a behaviourial barrier to smaller individuals. Like barrier nets, bar racks can be effective given proper hydraulic conditions. The U. S. Fish and Wildlife Service has prescribed close-spaced (typically 2.5 to 5 cm) bar racks and spilling for numerous hydro projects as the preferred method of fish protection. Studies conducted during 1990 and 1991 at a number of sites indicate that this method of fish protection may not be highly effective for bypassing outmigrating Atlantic salmon smolts. Additional studies are planned for the next few years to further evaluate the effectiveness of this protection system. These studies should be conducted prior to further consideration of bar racks for anadromous species.

Travelling (Through-flow, Center-flow, Drum, etc) and Fixed Screens - From a biological viewpoint, there is little difference between travelling and fixed screens except where heavy debris makes the travelling screen a better option for maintaining optimal hydraulic conditions. Screen, net and rack devices are similar, differing primarily in the type of medium used to repel fish. Provided that relatively low velocities can be achieved and debris clogging is not substantial, screens are effective barriers to fish passage. In the U.S., the approach velocity criterion for screens typically ranges from 12.2 to 30 cm/s depending on species and life stages (different agencies prescribe different criteria). As a result of the low velocity limits of such devices and the large flows typically occurring at hydro facilities, screening systems have not been used to a great extent. When screens are constructed, fixed screens are usually chosen because they are less expensive to construct and operate than travelling screens. In California, fixed screens are considered Best Available Technology (BAT) for protecting fish at small projects provided water velocities are low and highly effective debris management systems are employed.

COLLECTION SYSTEMS

Travelling Water Screens - Conventional travelling water screens have been modified for the collection and removal of fish. Survival following removal is dependent upon species, life stage, and method of screen operation. Since some mortality occurs as a result of impingement and removal from modified screens, this protection system cannot be deemed biologically acceptable at a given site without survival data for the species concerned.

Modified travelling screens are not frequently used because they are expensive to construct and maintain. Those presently in use filter small flows into cooling systems or other auxiliary flows.

Fish Pumps - Fish pumps may provide protection when coupled with fish bypass systems, such as angled screens and louvers.

DIVERSION SYSTEMS

Angled Screens - Angled fish diversion screens (travelling or fixed) leading to bypass and return pipelines have been investigated extensively. A conceptual design of a travelling angled screen system is shown on Figure 4. When relatively uniform flows and fairly constant approach velocities exist, a wide variety of species may be effectively guided along screens. Diversion is usually followed by piping or pumping. Relatively fragile species or life stages would not be expected to have a survival rate in excess of 70%, while hardier species should exhibit survival rates approaching 100%.

Some fishery resource agencies in the U.S. are skeptical that angled screens can effectively be applied to hydro projects. This has hampered the development of such screens. Angled rotary drum screens and submerged travelling screens are presently the "standards" for fish diversion at certain types of projects in the Pacific Northwest and should be considered further.

Angled Rotary Drum Screens - The same considerations that were identified for angled screens apply to angled drum screens. Extensive design and operational criteria are available as a result of model and field evaluations in the Yakima River Basin in Washington. A typical drum screen system is shown on Figure 5.

Seven angled drum screen installations are operational. They screen flows ranging from approximately 18 to 62 m^3/s [650 to 2200 ft^3/sec]. Other facilities are planned for the future. Experience indicates that the screens can be highly effective in diverting salmon fry and juveniles to bypasses under optimum hydraulic conditions (12.1 cm/s for fry; 24.4 cm/s for smolts). There have been problems with the seals between the screens and support structures (Figure 6) resulting in fish "leakage." These problems remain to be resolved.

Drum screens are relatively costly. Projects to date have cost between $22,000 and $43,000 US per m^3/s. The screens are limited to sites where water levels are relatively low and constant such that the screen remains 70 to 80% submerged at all times. At present, the largest screen diameter is 5.1 m. Where the hydraulic conditions can be met, angled drum screens represent an effective alternative for protecting fish.

Inclined Plane Screen - Inclined screens of several designs have been evaluated as a means of diverting fish upward toward surface bypasses. In a number of small applications, the screens have been reasonably successful. However, inclined screens have never been designed for large-scale application.

During 1990 and 1991, a passive pressure screen (Eicher screen) underwent prototype evaluation in the 2.7 m diameter penstock at the Elwha Hydroelectric Project near Port Angeles, Washington. This patented screen (Figure 7) successfully diverted various species and sizes of fish to a bypass pipe. The penstock velocity ranged between 120 and 237 cm/s at the time of the test. The latent survival values for each species/life stage were: coho salmon smolts - 99.4 and 98.6% in 1990 and 1991 respectively; coho pre-smolts - 99.2%; steelhead smolts - 99.4%; chinook fingerling smolts - 98.6%; chinook pre-smolts - 98.7%; steelhead fry - 96.9%; coho fry - 91.0% (Winchell 1990; EPRI 1992).

These results have generated much interest within the Northwest. While the Eicher screen should be considered as an effective technology for the diversion of salmonids in a penstock, it is believed that further refinement of the hydraulic flow conditions along the screen would enhance its potential for general application. EPRI is currently planning to conduct additional hydraulic model studies on the screen in 1992.

Submerged Travelling Screens - These screens (Figure 8) have been installed, or are being installed, at numerous hydroelectric projects in the Pacific Northwest to divert salmon outmigrants away from turbines and into gatewell bypasses. Despite many years of refinement in design and operation, many of the submerged travelling screens do not meet the desired performance efficiencies. Screen hydrodynamics and fish responses to the screens are not understood. These screens are not a cost effective form of fish protection at most hydroelectric projects.

Louvers/Angled Bar Racks - A louvre system consists of an array of evenly spaced, vertical slats (similar to bar racks) aligned across a channel at a specified angle and leading to a bypass (Figure 9). Louver effectiveness is species-specific and is strongly influenced by hydraulic conditions. Louvers are less effective than angled screens in diverting fish and are more sensitive to disturbances in flow direction and magnitude.

Results of louver studies vary by species and site. Most of the U.S. louver installations are in the Pacific Northwest and are not considered acceptable by many fishery resource agencies since they do not meet the 100% effectiveness criterion. However, numerous studies have demonstrated that louvers can be 80 to 95% effective in diverting a wide variety of species over a wide range of conditions (EPRI 1986). Ruggles *et al.* (1992) obtained excellent results using a floating louver system to divert Atlantic salmon and American shad at a power canal on the Connecticut River.

Louvers may potentially be used for a wide range of applications with several species and should not be considered ineffective due to the imposition of stringent success requirements. Additional research is warranted to refine their development.

Angled bar racks, that are installed in channelled flows, function as louver systems. To date, their effectiveness has not been evaluated. Many of these are situated such that flows enter the racks at angles approaching 90°. As such, the racks are no longer "angled" and fish are not guided to a bypass.

CONCLUSIONS

Relatively few of the fish protection systems that are described above should be considered for wide-scale application. Of the behaviourial barriers, strobe and mercury lights may be used to repel/attract a variety of fish species and should be considered when reviewing available options for fish protection. They can be evaluated at a reasonable cost and should be considered for use with other types of protection systems.

Sound projectors are relatively new fish protection devices. While the latest data on the biological effectiveness of projectors is encouraging, additional research is needed to identify their potential for protecting fish at hydro projects.

Of the physical barriers, barrier nets, bar racks and fixed screens are worthy of consideration as fish protection devices. All three devices share a common concern for debris loading and its inherent problems (structural loading, head loss, maintenance problems). Full-scale nets, racks and screens have been used successfully over a wide geographic range with various fish species, physical layouts and hydraulic conditions. While applying such devices on a site-specific basis usually requires design creativity, the extra effort will undoubtedly lead to the development of cost-effective solutions to fish passage problems at many sites.

Fish collection systems should only be considered at hydroelectric projects to screen auxiliary water supplies.

Angled screens, angled rotary drum screens, and louvers (or angled bar racks) are diversion systems that should be considered for wide-scale application. The Eicher screen is a new design and has been tested at only one site. It would be unwise to propose the wide-scale application of the Eicher screen until at additional prototype evaluations have been completed at other sites and with various species and life stages. The hydrodynamics of the Eicher screen are not well understood.

Leaks within the mechanical seals of angled drum screens must be corrected. Otherwise, these screens appear to be a viable alternative at sites where flow is low to moderate (ie., several hundred m^3/s), water levels are relatively constant (70 to 80% screen submergence) and water depth is not excessive.

Some agencies do not believe that angled screens and louvers work. While these devices may not meet criteria for effectiveness in all regions, they should be considered for future use because they do provide an 80 to 95% level of protection and very few other effective fish protection systems exist. The available systems are designed for specific conditions.

It is important that the individuals involved in the design of a particular system understand past applications, successes and failures, general layout requirements, hydraulic requirements, and fish behaviour. If the species of concern has not been studied previously, it would be wise to conduct flume or prototype studies to establish design and operational requirements. It would be unwise to mimic past designs as this approach to fish protection system development has been responsible for many of the past failures.

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Table 1. Categories of available fish protection systems/ devices used to prevent fish mortality at hydroelectric projects.

Category	Mode of Action	System/Device
Behaviourial Barriers	Alter or take advantage of natural behaviour patterns to attract or repel fish	Electric screens Air bubble curtains Hanging chains Strobe lights Mercury lights Sound Water jet curtains Chemicals Hybrid barriers
Physical Barriers	Physically block fish passage (usually in combination with low velocity)	Infiltration intakes Porous dike Wedge-wire screens Barrier nets Bar racks Travelling screens Stationary screens Rotary drum screens
Collection Systems	Actively collect fish for their return to a safe release location	Modified travelling screens Fish pumps
Diversion Systems	Divert fish to bypasses for return to a safe release location	Angled screens Angled rotary drum screens "Eicher screen" Submerged travelling screen Louvers

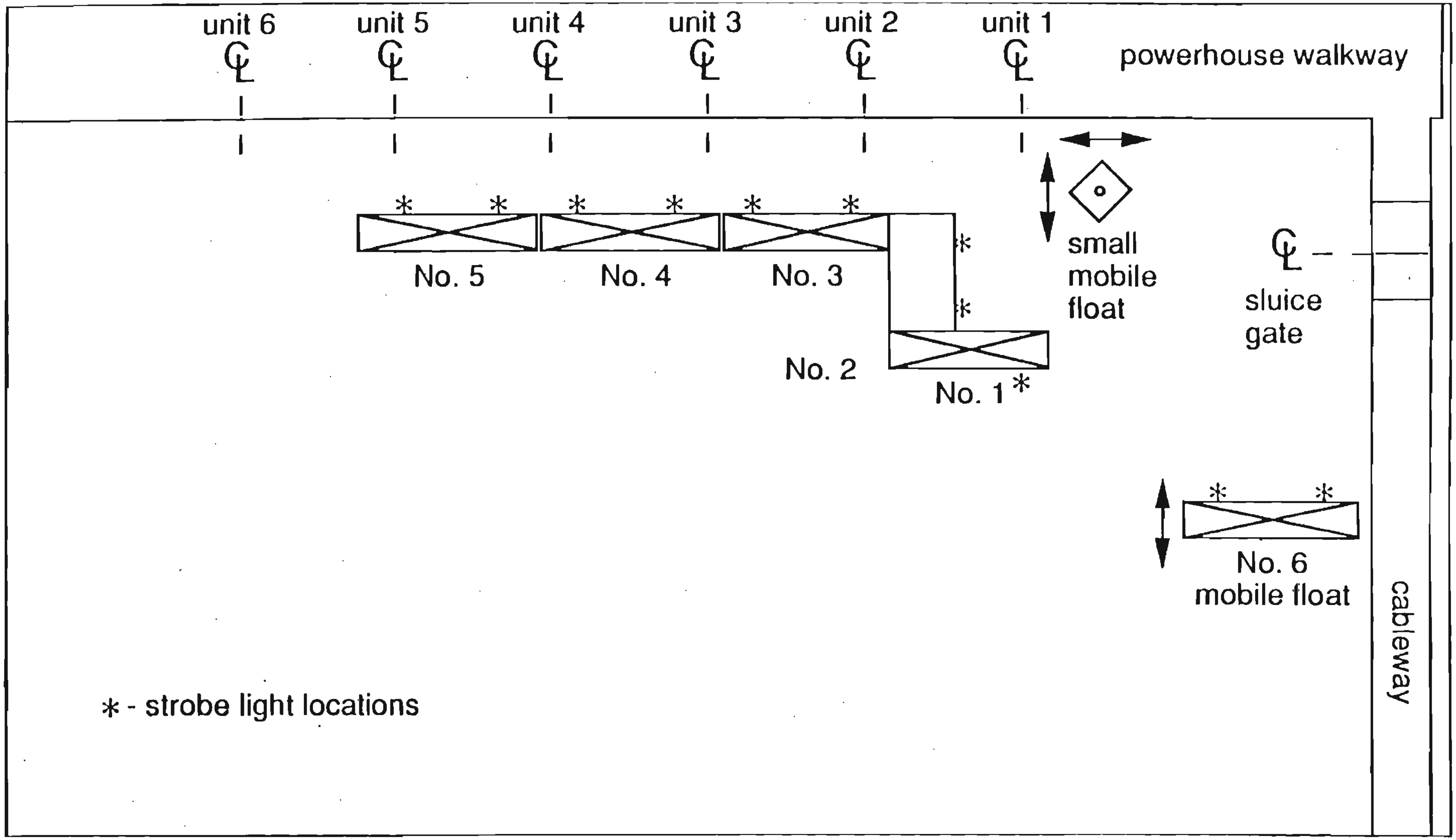

Figure 1. A schematic diagram showing the positions of the strobe lights used to divert juvenile shad outmigrants at the York Haven Hydro Project, on the Susquehanna River, Pennsylvania.

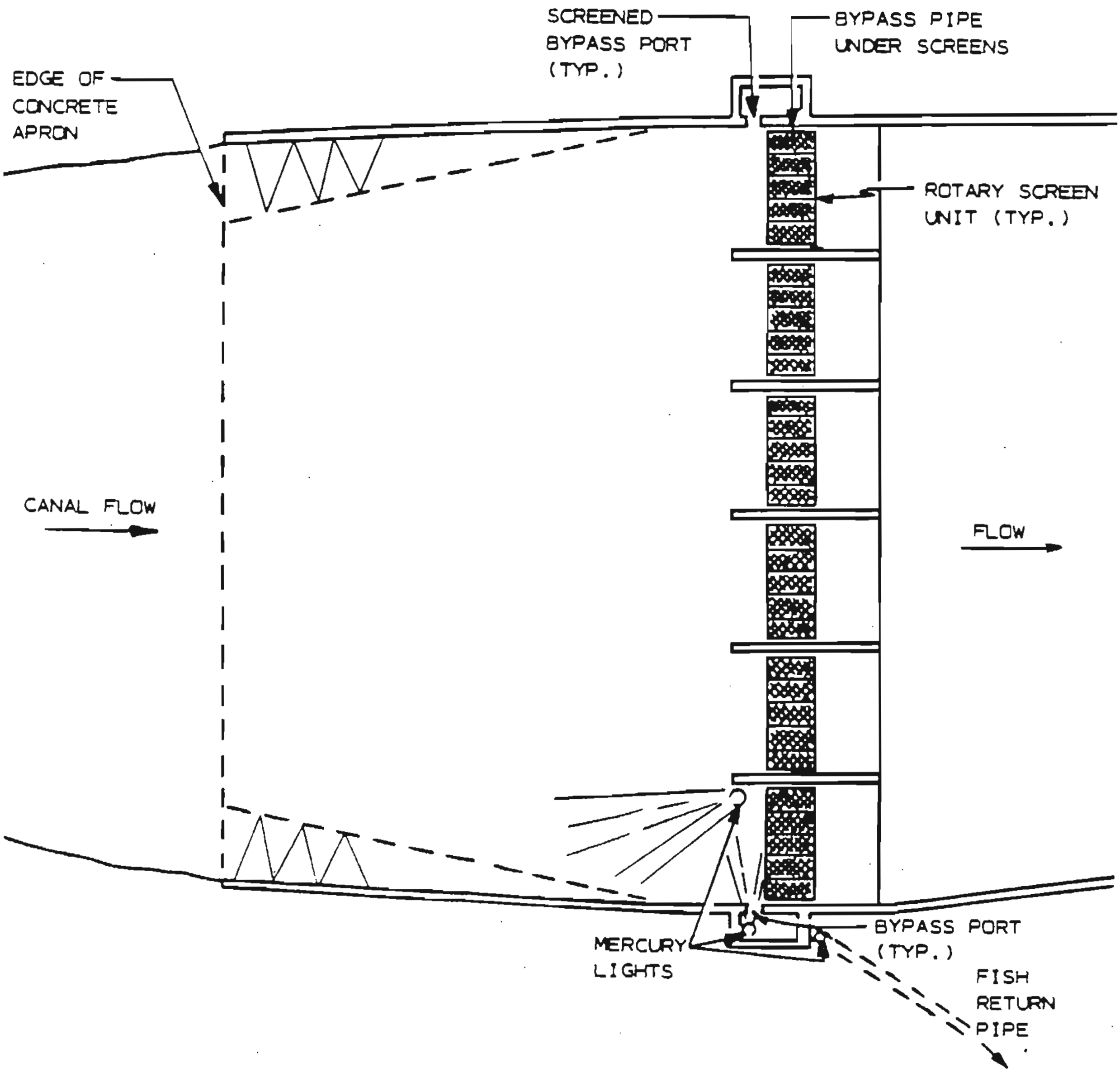

Figure 2. Plan view of the mercury light arrangement at the Wapatox Canal test site.

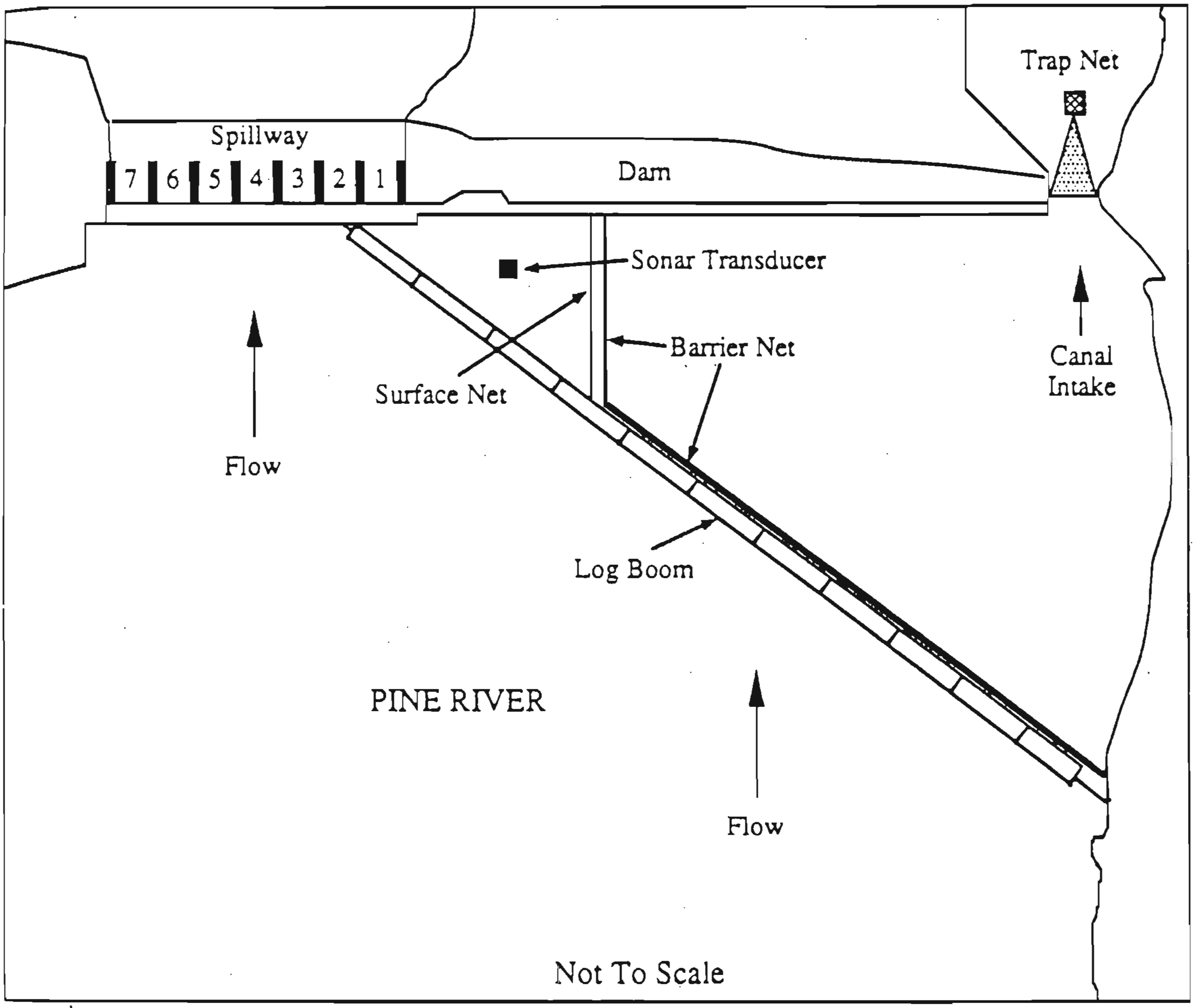

Figure 3. The barrier net system and evaluation equipment arrangement at the Pine Hydro Project, Wisconsin.

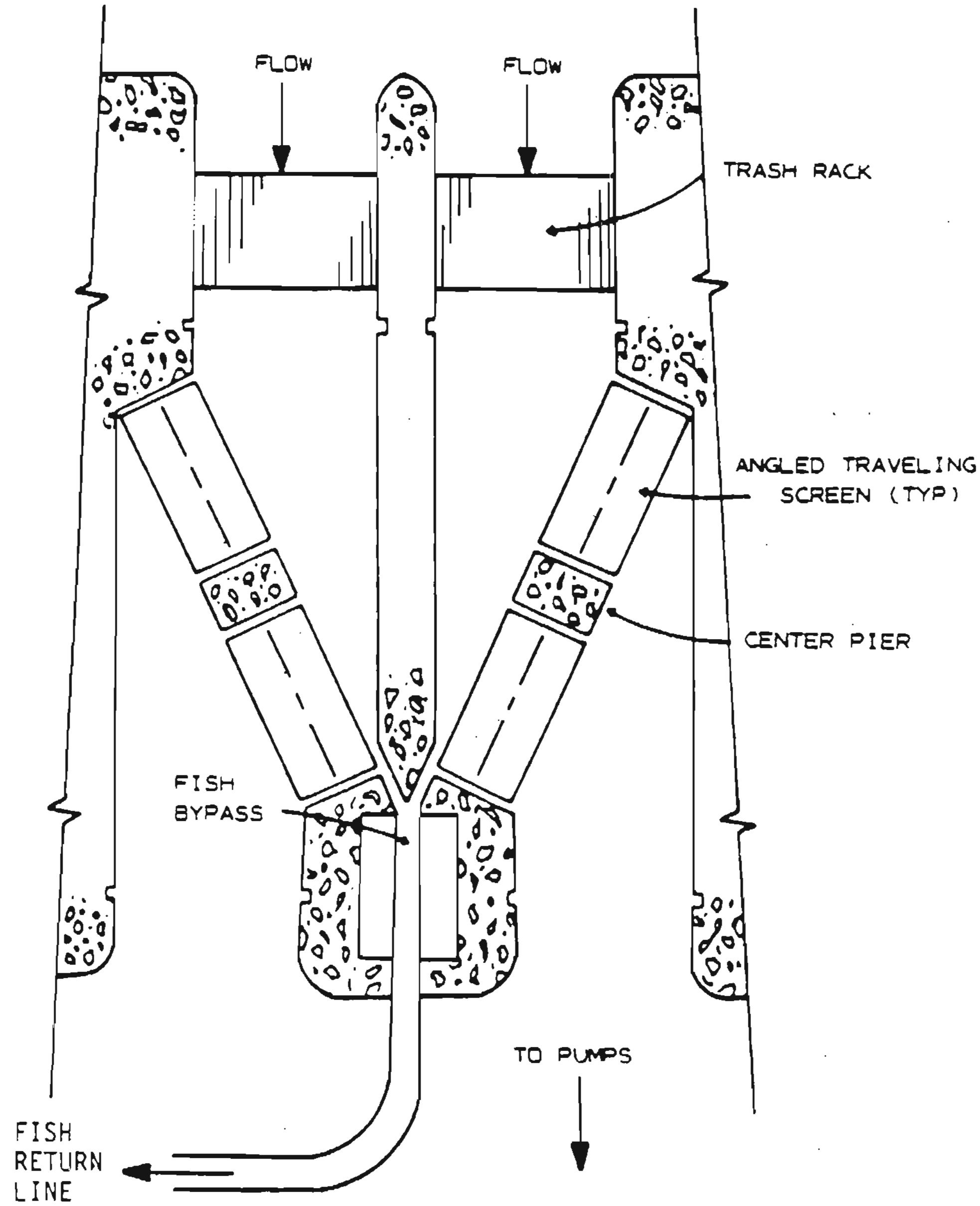

Figure 4. Conceptual design of a travelling angled screen diversion system.

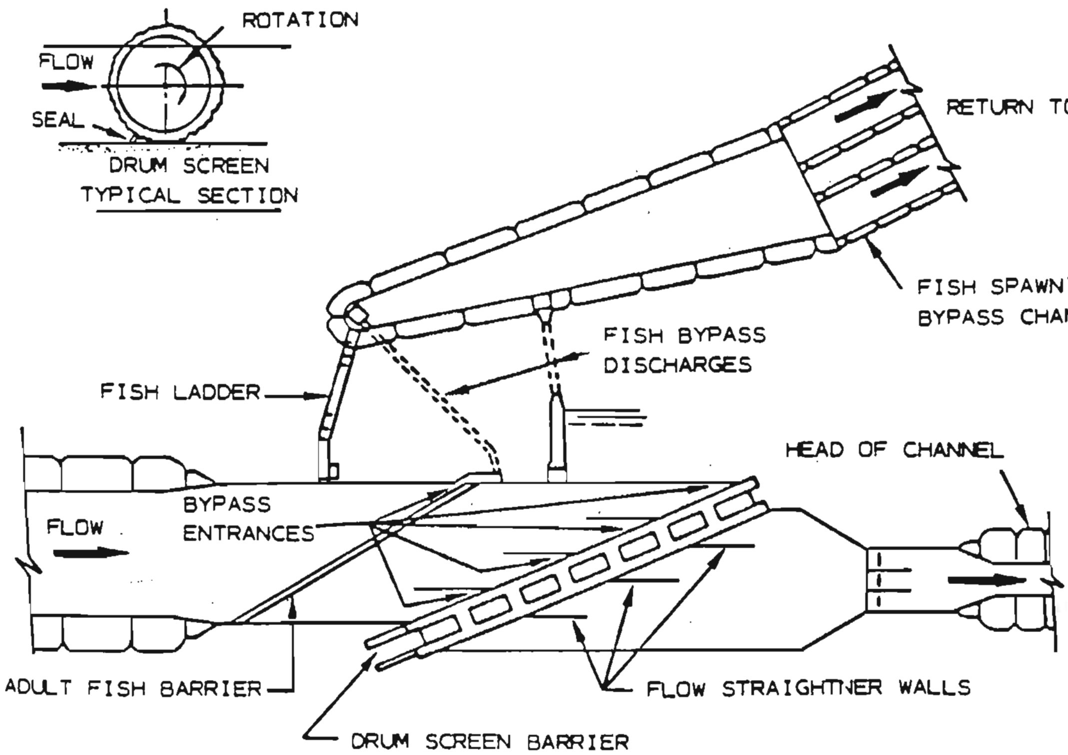

Figure 5. Angled rotary drum screens in the Tehama-Colusa Irrigation Canal, California. (U.S. EPA 1976)

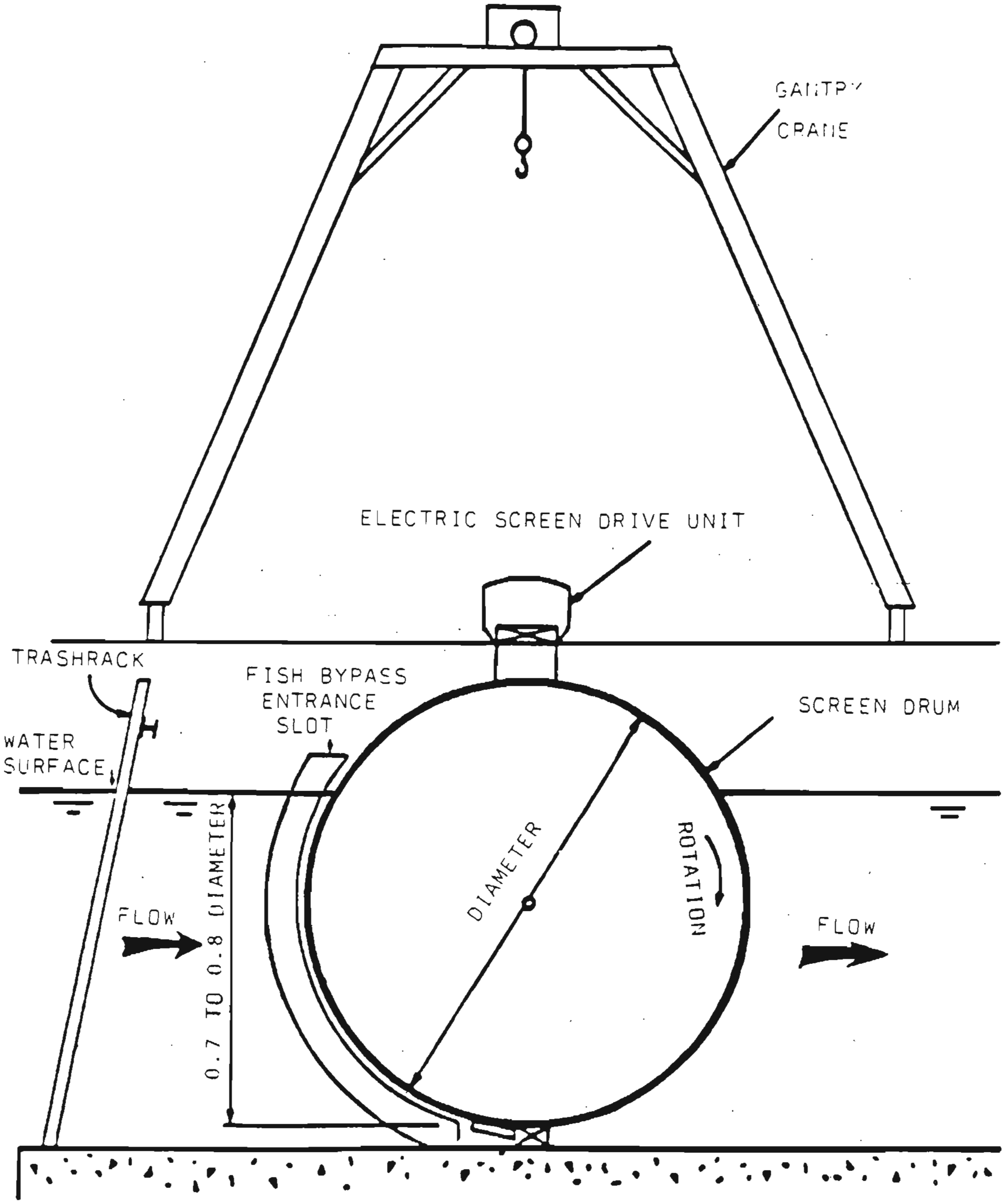

Figure 6. Side view of a drum screen .

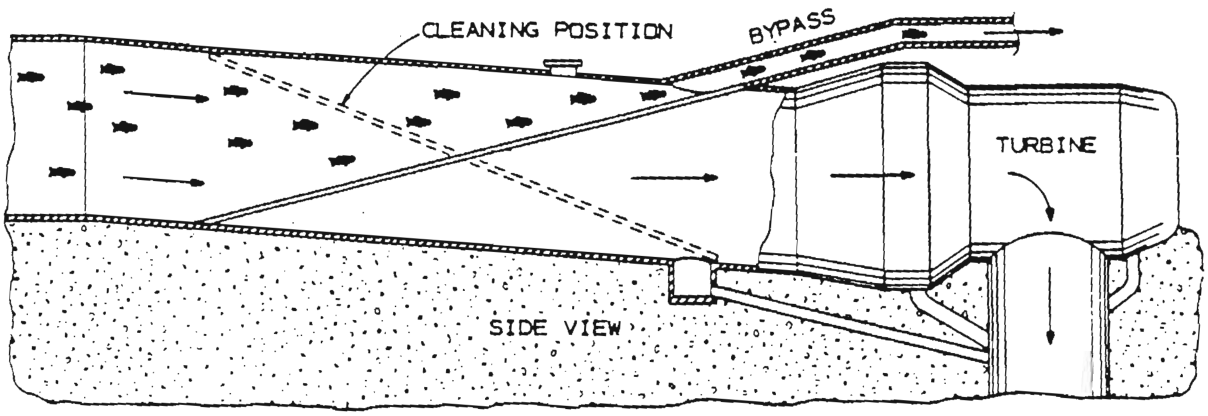

Figure 7. Conceptual design of a passive pressure screen (Eicher Screen). (Eicher 1985)

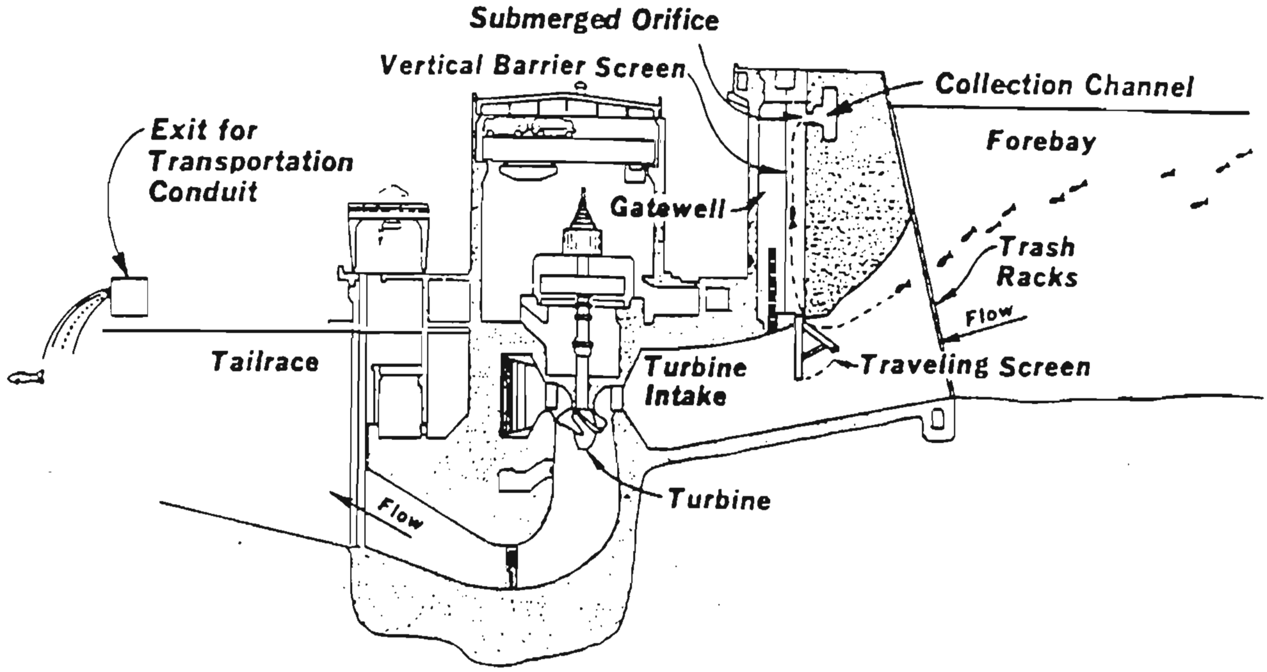

Figure 8. A typical submerged travelling screen. (Koski *et al.* 1985)

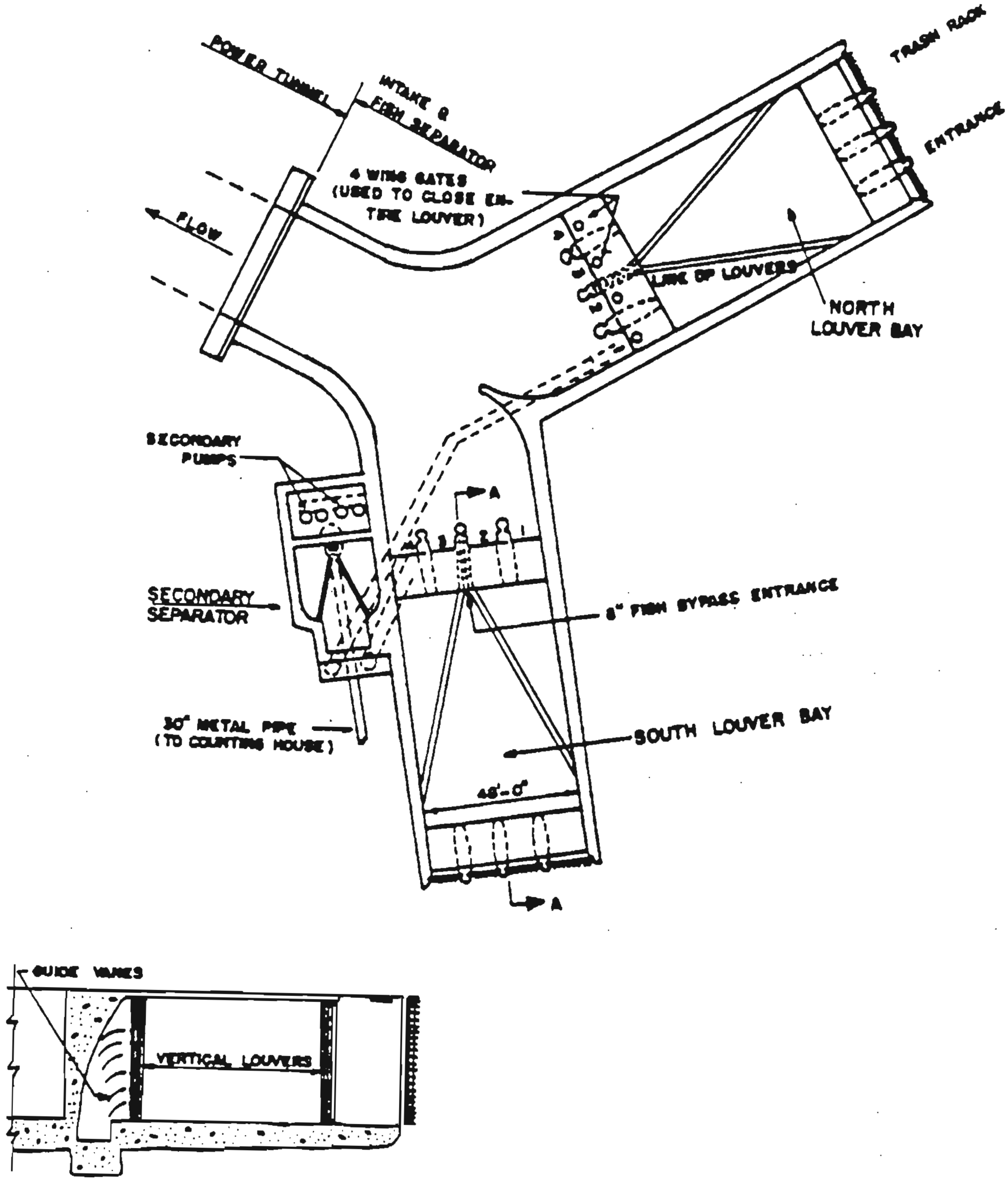

Figure 9. Mayfield Dam louver system. (Thompson and Paulik 1967)

THE USE OF FLOATING LOUVERS FOR GUIDING ATLANTIC SALMON (*Salmo salar*) SMOLTS FROM HYDROELECTRIC TURBINE INTAKES

by

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ABSTRACT

This paper describes the construction of a prototypic floating louver fish screen. Tests indicate that the screen is hydraulically stable in water velocities up to 1.0 m/s and has a guidance efficiency of between 50 and 100% for Atlantic salmon (*Salmo salar*) smolts. The mean guiding efficiency over the test period was 87%. No statistical differences in guidance efficiency were detected between 1.2, 1.8 and 2.4 m louver submergence depths.

INTRODUCTION

Mortality of downstream migrating Pacific and Atlantic salmon smolts may occur when they pass through hydroelectric turbines on their way to the sea (Ruggles 1980). Such losses represent a reduction in the population at a life-history stage that does not allow for normal biological compensatory regulations to mitigate against the losses (Ricker 1954; Lindroth 1965; Larkin 1970; Royce 1973). Therefore, mortality occurring at the smolt stage adversely affects the rate of adult recruitment, and hence the yield from any specific salmon stock originating from spawning areas upstream of a hydroelectric development.

On the Connecticut River in the eastern United States an extensive effort to rehabilitate Atlantic salmon within the river system has created a concern that migrating smolts may suffer turbine induced mortality at five mainstem dams. Northeast Utilities Service Company owns and operates the lowermost two dams on the river. In 1989, the company began to explore alternatives for excluding Atlantic salmon (*Salmo salar*) smolts and anadromous clupeids (from hydroelectric turbine intakes. After reviewing the fish screening technologies that appeared to have promise for excluding downstream migrants from the large flows involved, it was decided to develop and test a new concept based on the louver fish deflector (Bates and Vinsonhaler 1957).

Since its invention in 1955, the louver fish deflector has proven effective in diverting many species of fish under both experimental and prototype situations. Louvers comprise a series of vertical slats placed in a diagonal line across the path of downstream migrating fish. Each slat is placed at right angles to the direction of flow. Fish tend to avoid the slats while continuing downstream and thus are guided to a bypass at the downstream end of the louver line. The louver fish screen is the only behavioral fish screening technique that has proven effective in removing fish from turbine intakes.

The cost of screening the entire water depth with louvers has been a deterrent to their more widespread use in the US and Canada. The concept of floating louvers that would screen only the surface flow is based on the observation that salmon smolts and downstream migrating anadromous clupeids tend to migrate near the water surface. Not only would the cost of fish screening be reduced, but a floating louver array could be used in situations where site conditions preclude a more conventional installation. In May 1990, a prototype floating louver fish screen was tested in a power canal adjacent to the Holyoke Dam located

140 km upstream of the mouth of the Connecticut River. The tests were conducted with radio tagged Atlantic salmon smolts. Tests were designed to evaluate the practical hydraulic feasibility of the structure and to document Atlantic salmon smolt guiding behaviour with relatively shallow louver submergence (1.2 to 2.4 m).

DESCRIPTION OF FLOATING LOUVERS AND THE TEST SITE

The louver array was composed of a series of floating frames that supported vertical louver panels submerged to a depth of 2.4 m (Figure 1). The installation in the power canal utilized 86 louver panels supported by 29 floating frames. Each floating frame was made of four wooden timbers, styrofoam flotation blocks and steel guides that accepted the louver panels. Each louver panel was constructed of four horizontal polypropylene guide plates that supported vertical polypropylene louver slats at 7.6 cm spacing. The louver slats were 2.4 m long, 6.4 cm wide and 9.5 mm thick. The floating frames were attached to a 2.54 cm diameter cable that spanned the canal at a 14^{o} angle to the flow. Adjacent frames were attached to each other by threaded rods and wooden splines. Each floating frame supported two louver panels in the centre of the frame, plus one-half of two louver panels that spanned adjacent frames. The entire louver array was 157 m long and ended in a 4.6 m gap between the downstream end of the louver line and the bank of the pier canal. The depth of louver submergence was varied by moving the louver panels vertically within the steel guides on the floating frame.

The power canal was 45 m wide, 6 m deep and had a hydraulic capacity of approximately 200 m^3/s. The louver array was installed 100 m downstream of a gatehouse that controlled the flow entering the power canal. The gatehouse employed bottom opening gates that introduced most of the flow at a depth about 1 m below the bottom of the 2.4 m maximum submergence depth of the floating louvers. Average water velocity at a depth of 1 m in the canal upstream of the louver array ranged from 0.65 to 1.0 m/s while the canal flow ranged from 105 to 147 m^3/s.

METHODS

Experiments were conducted over a four week period from May 18 to June 12, 1990. Hatchery reared Atlantic salmon smolts, 21 to 28 cm in length, were used as test fish. These were larger specimens selected from one year old smolts reared at the White River National Fish Hatchery in Bethel, Vermont. Radio tags were attached to the left side of each fish immediately posterior of the dorsal fin. Tagged fish were held from one to four days before release upstream of the louver array. The tags were approximately 29 mm long (excluding antenna), 9 mm in diameter and weighed approximately 2 g. They were manufactured with 12 frequencies (40.01 - 40.15 MHz, excluding 40.02, 40.06 and 40.10 MHz) and four pulse rates (60, 70, 90, and 110 pulses/minute). Specified battery life was 28 days. The tags had external antennae.

Radio receivers were located at four locations along the louver line, at the downstream end of the louver array, and at a point 100 m downstream of the opening. The receivers permitted the simultaneous tracking of up to 12 individual tagged fish as they encountered the louver array. Personnel monitored the receivers until all radiotagged fish had either passed through the louvers or had been guided to the 4.6 m gap between the downstream end of the louver line and the bank of the power canal. Fish that passed through the gap were monitored by a whip antenna that was screened by a grounded sheet-metal hood to prevent signals outside the gap area from being recorded.

The tagged fish were released at either of two locations. The first release point was located below the gatehouse, 100 m upstream of the louver array, on the true right bank (looking downstream) of the power canal. These fish had to cross to the left bank of the canal to reach the bypass gap at the downstream end of the louver line. Hence, guided fish were theoretically exposed to the entire 157 m long louver array. The second release point was above the gatehouse that controlled flow into the canal. Fish were released from a log boom that was located 25 m upstream of the gatehouse (Figure 2).

Fish were released in 10 lots of 9 or 10 fish each. Each test lot was composed of 2 groups of 4 or 5 fish that were released together from a 1 m x 1 m x 1 m release pen constructed of 1.27 cm galvanized mesh. Tagged smolts were left in the release pen for 5 minutes before a door on the downstream side of the pen was opened. Most of the smolts slowly left the release pen tail first within a few minutes. If any fish remained in the pen after a 5 minute interval, they were forced to leave by slowly lifting the pen out of the water. The second group, made up of the remaining 4 or 5 tagged fish, was released in the same manner, usually after the first group had passed downstream of the louver array.

RESULTS

The floating louver array guided between 50 and 100% of the radio tagged Atlantic salmon hatchery smolts to the downstream end of the louver line (Table 1). The mean guiding efficiency over the entire test period was 87%. No statistical difference in guiding efficiency occurred between louver submergence depths of 2.4, 1.8 and 1.2 metres. Even with the louver panels removed, the remaining submerged steel guide frames spaced about 1.8 m apart guided 75 % of the test fish. With the louver array removed from the power canal (the control situation) 10% of test fish passed through the 4.6 m wide between the downstream end of the louver line and the left bank of the power canal.

The floating louver array was hydraulically stable in water velocities of up to 1.0 m/s. The installation proved structurally rugged and tended not to collect debris, most of which was guided to the downstream end. The louver line caused some head loss in the power canal, but it was not measured. A backwater build-up increased progressively upstream until at the upper end of the louver line very little water flowed through the louver bars. Conversely, a greater proportion of the flow passed through the downstream end of the louver line. As a result, velocity measured 0.3 m upstream of the louver array increased from the upstream to the downstream end of the louver line by a factor of 2.5 (Table 2). The floating louvers proved easy to build, install and maintain. Construction costs were approximately $150.00 per linear foot.

DISCUSSION

Although the cost of radio tags limited the extent of replication, the results from these preliminary tests show that floating louvers provide a new alternative for preventing Atlantic salmon smolts from entering hydroelectric turbine intakes. The results confirm conclusions drawn from 5 years of louver research in Nova Scotia, Canada, that louver panels need not exceed a depth of 2 m to successfully guide Atlantic salmon smolts (Ducharme 1972). From a cost and operational point of view, the shallower the louver submergence the better. On the basis of these preliminary data, submergence depths of less than 2 m may prove successful for guiding salmon smolts. Research should be conducted to determine the minimum effective submergence depth since this criteria is important in determining the wide scale application of floating louvers.

Another area for research involves determining the maximum acceptable louver slat spacing. Wider slat spacings reduce head loss, debris accumulation and cost of construction and operation. Research suggests that spacings greater than 0.3 m may be effective in guiding Atlantic salmon smolts (Ducharme 1972). The somewhat surprising results that 75% guiding efficiency could be achieved with only the guide frames of the louver array remaining in the power canal suggest further research is justified.

Some of the smolts that were introduced downstream of the gatehouse were guided along the 157 m louver line before reaching the downstream gap. This represents a considerably longer guiding distance than exists at other louver installations. In theory, the distance guided is a function of the approach velocity, the swimming speed of the fish to be guided and the angle of the louver line in relation to the direction of flow. The approach velocity is made up of two components, one parallel to the line of louvers and the other at right angles to the individual louver slats. The latter must be overcome by the swimming speed of the fish and is a function of the approach velocity and the angle of the louver line. As long as the velocity at right angles to the louver slats is less than the cruising speed of the fish (Brett *et al.* 1958), the length of louver line that a fish must traverse before reaching a bypass is not critical.

The louvers were not attached to a fish bypass, hence problems associated with this critical element in a downstream fish passage facility were not present. The width of the gap at the downstream end of the louver line exceeded the 46 cm wide opening found to be necessary for schooling species of Pacific salmon (Ruggles and Ryan 1964). In addition, water velocity continued to accelerate along the entire length of the louver line, therefore, there was no reduction in flow velocity at the downstream end of the louver line. When such reductions in flow velocity occur, louver fish guiding efficiency is reduced (Ruggles and Ryan 1964; Ducharme 1972).

The effect of radio tagging on smolt response to the louver array is difficult to assess. However, guiding results surpassed those previously reported for salmonid species (Bates and Vinsonhaler 1957; Ruggles and Ryan 1964; Ducharme 1972). Final evaluation will have to await testing with natural runs of wild Atlantic salmon smolts. However, based on previous tests using both wild and hatchery juvenile salmonids at experimental and operating louver sites, smolt guiding efficiency of the floating louver fish screen is expected to exceed 80 %.

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Table 1. Summary of the Holyoke floating louver evaluation using radio-tagged Atlantic salmon smolts, May 18 through June 12, 1990.

Release Date	Lot #	Time Start	End*	Louver Depth (m)	Release Location	# of Smolts Released	# of Smolts Guided	% Guided
May 18	1	1132	1214	2.4	Downstream of canal gatehouse	10	8	80
May 23	2	1550	1632	2.4	Upstream of canal gatehouse	9	9	100
May 24	3	1039	1119	2.4	Upstream of canal gatehouse	10	10	100
May 25	4	1118	1159	1.8	Downstream of canal gatehouse	9	8	89
May 30	5	1250	1315	1.8	Upstream of canal gatehouse	10	9	90
May 31	6	1151	1214	1.2	Downstream of canal gatehouse	10	5	50
May 31	7	1440	1517	1.2	Upstream of canal gatehouse	10	10	100
June 6	8	1248	1329	**	Upstream of canal gatehouse	10	8	80
June 6	9	1339	1401	**	Downstream of canal gatehouse	10	7	70
June 12	10	1244	1255	***	Upstream of canal gatehouse	10	1	10

* End time defined as the time the last smolt was detected at the downstream end of the louver array.
** Louver frames in place, louver panels removed.
*** Both louver panels and frames removed.

Table 2. Summary of water velocity along the floating louver array taken 0.3 m upstream of the louver slats and at a depth of 0.9 m.

Distance from Downstream End (m)	Canal Flow 105 m³/s	Canal Flow 116 m³/s	Canal Flow 119 m³/s	Canal Flow 147 m³/s	Mean Velocity (m/s)
154	1.2	1.2	1.5	1.8	0.44
136	1.6	1.4	2.0	2.6	0.56
117	2.0	1.7	2.4	2.6	0.67
99	2.0	2.2	2.6	2.7	0.79
81	2.2	2.5	2.5	3.0	0.80
63	2.6	3.1	2.7	3.2	0.88
45	2.9	3.1	2.6	3.2	0.91
30	3.0	3.3	2.8	3.3	0.94
23	3.3	3.3	3.0	3.3	0.97
16	3.5	3.3	2.8	3.6	1.00
8	3.1	3.0	3.1	3.9	1.00
1	3.1	3.9	3.3	3.5	1.10

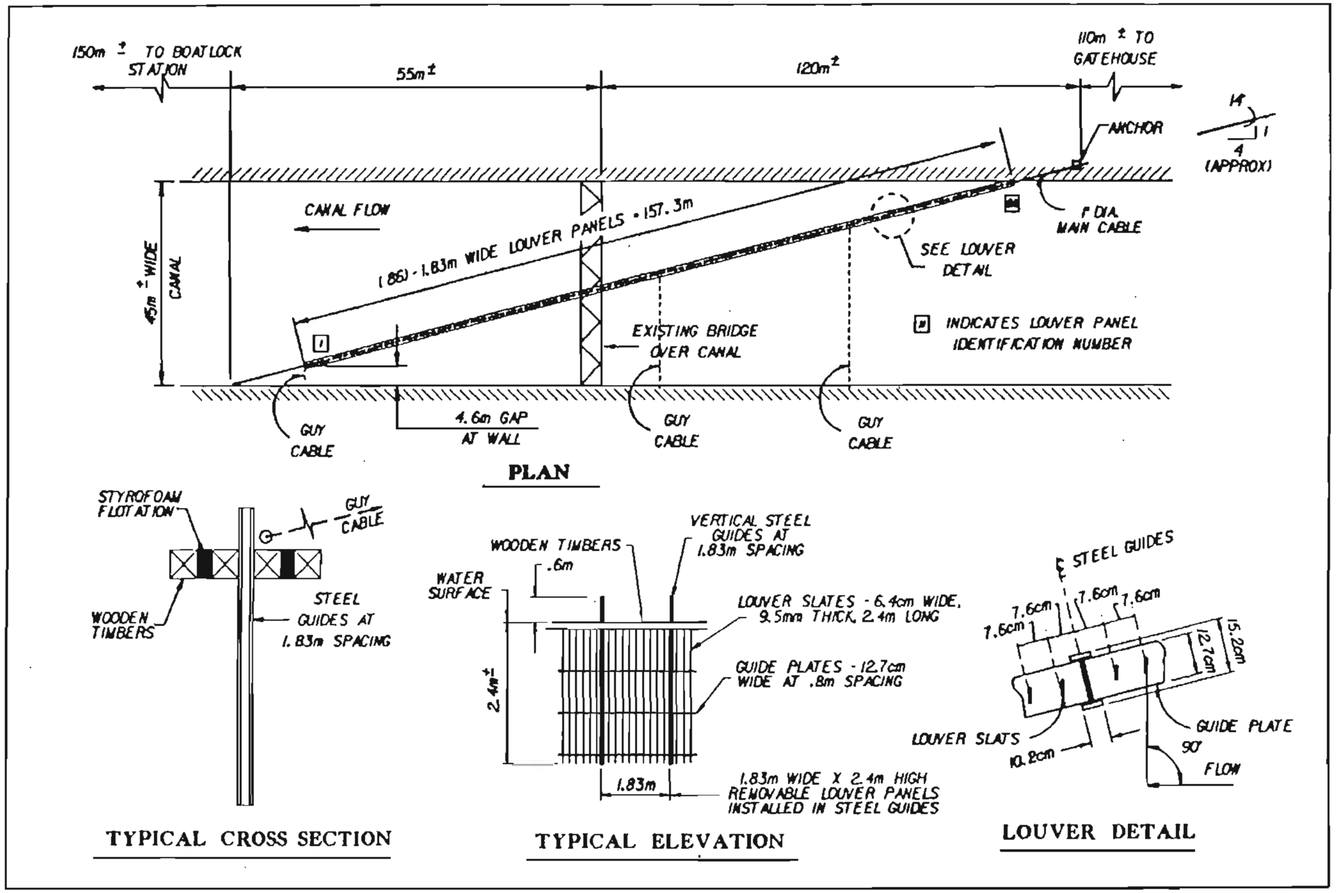

Figure 1 Design details of the Holyoke floating louver.

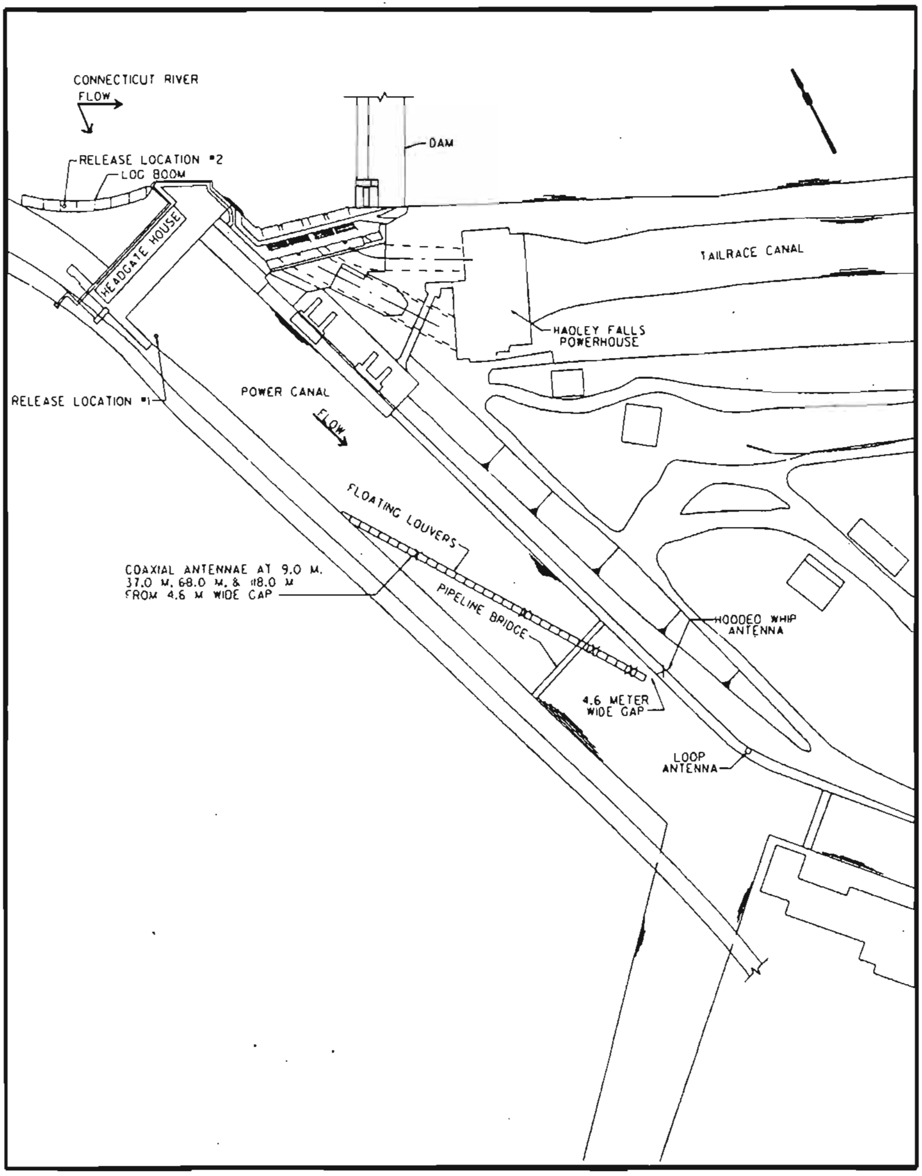

Figure 2 Site plan showing the locations of the radio antennae and smolt release locations in the Holyoke Power Canal.

FISH BEHAVIOURS RELATING TO PASSAGE AT HYDROELECTRIC DAMS

ANADROMOUS FISH BEHAVIOUR IMPORTANT FOR FISH PASSAGE

by

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ABSTRACT

An understanding of the behaviour of target fish species is necessary to properly design, locate, and operate a successful up- or downstream fishway for anadromous migrants. Important fish behaviours are seasonal and daily timing of migration; rheotaxis and near field behaviour; stimulus-response behaviour; swimming capability; shoaling behaviour; response to physical environmental factors (e.g., illumination, sound, water depth, current velocity, and structure); response to chemicals; and response to biological factors (e.g., competition for space and response to predators). This report reviews information on migrant fish behaviours using examples from behaviour of eastern anadromous species, particularly Atlantic salmon (*Salmo salar*) and American shad (*Alosa sapidissima*).

INTRODUCTION

The past century of fishway development has focused on the engineering aspects, particularly fishway hydraulics and site engineering. Only recently has fish behaviour, other than swimming capability, been recognized as important for fishway design and operation (Clay 1961, Bell 1980, Orsborn 1987, Katopodis 1991).

The most serious effort to examine behaviour of adult anadromous migrants in fishways was done in the 1950s and 1960s at the Fisheries-Engineering Research Laboratory located at Bonneville Dam on the Columbia River (Collins and Elling 1961, Trefethen 1968). A variety of experiments conducted, mostly with adult salmonids in experimental flumes, resulted in behavioural information on swimming abilities, responses to abiotic environmental factors, and behaviour relative to various structures used for fish passage. For many scientists, the results emphasized the value of behavioural information and of the need for collaborative efforts in fishway research between fish behaviourists and hydraulic engineers.

Attempts to provide up- and downstream passage for the diverse group of anadromous species on the Atlantic coast have produced unpredictable results. This situation emphasizes our lack of knowledge about the behavioural requirements for passage of most eastern anadromous migrants.

The present paper is an overview of the types of behavioural information that are important for designing, locating, and operating fish passage facilities. The discussion focuses on passage situations for anadromous migrants at hydroelectric dams. Most examples involve eastern anadromous species, particularly Atlantic salmon (*Salmo salar*) and American shad (*Alosa sapidissima*).

MIGRATION TIMING

SEASONAL PATTERN

The seasonal movement pattern of up- and downstream migrants past a dam reveals the time that fish are present and need passage. This information (usually in the form of calendar period) is always called for when planning a fishway (Rizzo 1969). Examples of efforts to gather this information on eastern anadromous fishes are Saila *et al.* (1972), Rideout *et al.* (1979), Cooke (1990), and RMC Env. Serv. (1991).

Information on seasonal timing and river discharge levels show the migratory routes available at hydroelectric dams and the period when fishways should operate. This information is critical for successful fishway operation (McMenemy and Kynard 1988).

Proximate environmental factors that affect the timing of riverine migrations are photoperiod, daily light level, lunar phase, river flow, and river temperature (Groot 1982, Solomon 1982). For juvenile American shad and blueback herring (*Alosa aestivalis*) during years with normal river discharge, the major downstream migration period is defined by lunar phase and water temperature (O'Leary and Kynard 1986). Once downstream movement of these juveniles begins in the fall, emigration intensity is enhanced by dramatic increases in river discharge (Barnes-Williams Env. Consul. 1988). Similarly, the timing of downstream movement of Atlantic salmon smolts is related to stream temperature (Ruggles 1980). The situation is complicated because smolt migration in a single river can occur at different temperatures in different years (Bakshtansky *et al.* 1976).

Studies of seasonal movement patterns of migrants, when both migrants and non-migrants are present, should use a passive method that captures or observes only migrating fish. Passive methods used successfully on the east coast are (1) floating inclined-plane traps (McMenemy and Kynard 1988), (2) floating auger traps (N. Ringlerm, pers. comm.), (3) stream weirs and counting fences (Chadwick 1981, Orciarri *et al.* 1987), and (4) visual/video observations at fishways and dams (Richkus 1974, O'Leary 1988). Underwater hydroacoustics, which was used successfully to monitor seasonal abundance of fish runs at dams on the Columbia River (Magne 1983, Raemhild *et al.* 1985), has not been used to monitor seasonal timing of fish on the east coast.

DAILY PATTERN

Daily activity may be diurnal (active during the day), nocturnal (active at night), crepuscular (active at dawn and dusk), or dualistic (dual phasing of activity; Eriksson 1978). Activity patterns of anadromous migrants are highly variable. The daily pattern varies among migrants of sibling species, e.g., five species of *Oncorhynchus* (Groot 1982) and three species of *Alosa* (Richkus 1974, O'Leary and Kynard 1986).

Daily activity can vary during the migration. Atlantic salmon smolts moving early are mostly nocturnal, while late migrants also move in the day, particularly in the afternoon (Thorpe and Morgan 1978, Solomon 1982). O'Leary and Kynard (1986) found similar changes during the migration of juvenile migrant American shad.

Migrant juvenile blueback herring and alewife are active in the day, particularly in the afternoon (Kissil 1974, Richkus 1975, O'Leary and Kynard 1986, Barnes-Williams Env. Consul. 1987). Some juvenile American shad move in the afternoon, but most juveniles are nocturnal (O'Leary and Kynard 1986).

Activity patterns of adult migrants are also highly variable. Adult Atlantic salmon in the open river move upstream mostly at night (Thorpe 1988). Swimming speed of adult American shad show crepuscular and diurnal activity (Leggett 1976, Katz 1986). Adult blueback herring passage at dams peaks in the afternoon (Cooke 1990). Early migrant sea lampreys (*Petromyzon marinus*) are nocturnal, while late migrants move both day and night (Steir and Kynard 1986).

The daily activity pattern of migrants identifies the daily period when passage efforts for a species should be focused. For situations where adult fish must pass long fishways and passage may take longer than one daily period of activity, information on the daily activity cycle can alert fishway designers for potential dropback of fish at night.

The addition of artificial illumination at night in fishways may allow fish active in the day to better maintain position or to continue passage (if their activity cycle is not endogenous). The activity cycles of American shad (Katz 1978) and alewife (*Alosa pseudoharengus*) (Richkus and Winn 1979) are not endogenous, thus artificial light may be useful for increasing their activity at night. Preliminary experimental results indicate artificial illumination increases activity and use of fast water habitat of adult American shad at night (E. Theiss and B. Kynard, unpub. data). Artificial light is used in darkened fishway entrances and channels to facilitate movement of adult Pacific salmon (*Oncorhynchus* spp.) through the fishway system at Bonneville Dam (Turner *et al.* 1984).

Artificial lights must be used with care at fishways. Smith (1985) and Fields (1964) discuss several situations where Pacific salmonids avoid artificial illumination at fishways and are prevented from entering or moving up fishways at night (the preferred activity period). Fish avoidance seemed stimulated by the abrupt change from darkness to bright illumination.

Some upstream fishways may cause the exclusion of behavioural phenotypes that will only move upstream during the natural activity cycle. This could be a problem for passing some adults of nocturnal species, like Atlantic salmon (Thorpe 1988), in highly artificial fish passes, such as fish elevators, that only operate during the day.

RHEOTAXIS AND NEAR FIELD ORIENTATION

Most fish use visual and rheotactile stimuli (water displacement detected by the lateral line system) to direct their movements in the near field (local area) environment (Smith 1985). Rheotaxis, the orientation of fish to water current, depends on appropriate visual, tactile, or water displacement stimuli (Arnold 1974). Visually oriented species use visual reference points, e.g., structure, bottom features, etc., to direct their movements in the near field environment. When illumination levels decline below a threshold level, the optomotor response (optical reflex) is not stimulated. Then fish may orient using rheotactile stimuli from nearby water currents or tactile stimuli from touching reference structures.

Adult migrant American shad use visual stimuli to detect and avoid gill nets during the day (Leggett and Jones 1971). Even at night, some fish still avoid nets in the near field (about 1 m). American shad may be using the inner ear or lateral line to detect acoustic or water movement stimuli caused by water flowing past the strands of net.

Water clarity affects the usefulness of vision for orientation in the near field. Loss of visual cues during periods of high turbidity may cause adult Atlantic salmon to stop upriver movement (Thorpe 1988).

Rheotactic orientation may change during migration if the social organization changes. Individual and small groups of Atlantic salmon smolts leaving territories orient lateral to the current and are close to the bottom. As school size increases to more than eight, fish orient into the current and become pelagic, swimming in the deep channel near the water's surface (Bakshtansky *et al.* 1982).

STIMULUS-RESPONSE BEHAVIOUR

The relationship between a fish and its environment is in the immediate control of a behavioural response (swimming movement) to environmental stimuli. A stimulus may promote some actions (by triggering, alerting, or orienting) and suppress others (by arresting, desensitizing, or disorienting). Fishways contain many types of stimuli, e.g., illuminated and dark areas, high velocity and low velocity water, turbulent water and directional flow, etc. At present, we have a poor understanding of migrant responses to any physical stimuli in fishways.

We can understand the relationship between migrant behaviour and the physical environment in fishways by quantifying the stimuli and the swimming movements of fish as they encounter stimuli. The speed, direction, and duration of the swimming movement can then be used to model the stimulus-response relationship. Anderson (1988a) proposed a similar approach for understanding behavioural barriers to guide downstream migrants.

Turbidity affects the stimulus-response distance for visual stimuli. Juvenile migrant American shad strongly avoid a strobe light stimulus. High levels of turbidity in a river can reduce the stimulus-response distance and make the stimulus ineffective for guiding fish (Stone & Webster Env. Serv. 1991).

SWIMMING CAPABILITY

Fish movement upstream in a fishway is stopped if current velocities exceed the swimming capability of the fish. For this reason, information about swimming speed has long been recognized as necessary for fishway design and operation (Clay 1961, Bell 1980).

Although many species have been studied for cruising speed (maintain for hours), sustained speed (maintain for minutes), and burst speed (maintain for 5-10 seconds), most eastern anadromous species have not been rigorously studied (Bell 1986). Extensive studies of eastern species may not be necessary because the swimming performance of most species is similar for fish of similar length (Wardle 1979, Wardle and Videler 1980) and body form (Beamish 1978, Lindsey 1978).

Even if swimming capability is known for target species, it is difficult to select the proper maximum velocity for a fishway. Swimming ability changes during migration because of abiotic factors (water temperature, dissolved oxygen, chemicals, etc.) and biotic factors (physiological condition of migrants). For example, increased temperatures reduce the cruising speed of young salmonids up to 50 percent (Brett *et al.* 1958).

Jumping ability gives fish an additional behaviour to use when passing through difficult areas of upstream fishways (Clay 1961). The Atlantic salmon is the only eastern species that jumps. For successful upriver passage of non-salmonid adults, fishways must have the appropriate environment and hydraulic conditions.

SHOALING BEHAVIOUR

The migrants of many species of eastern

anadromous fish form social groups called shoals. Some shoals exhibit schooling behaviour (synchronized and polarized swimming). Behaviour of fish shoals was reviewed by Pitcher (1986). Aspects of fish behaviour in shoals that are important to consider for passage in fishways are (1) shoaling fish use vision and the lateral line to orient and maintain position, (2) inter-fish distance is directly related to fish size, (3) amplitude of tail beat is the most important variable for determining minimum lateral space, (4) directional heading is provided by the fish directly ahead, (5) some fish are leaders, others are followers, and (6) fish in small schools are more timid, more excitable, and have higher respiratory rates than fish in large schools.

Clupeids spend most of their lives in a shoal (Blaxter and Hunter 1982), but shoaling behaviour during riverine migrations appears variable. Schools of adult American shad break up during upriver movement with fish moving singly or in loose aggregations (Leggett and Jones 1971, Katz 1986, Witherell and Kynard 1990, B. Kynard, unpub. data). When upriver movements become blocked by a natural barrier or dam and fish are unable to find passage, schools reform. Schooling in this situation may be an alarm or fright response to a noisy, turbulent, and confusing environment. Juvenile alosids gather into shoals for downstream migration (Richkus 1974, O'Leary and Kynard 1986, B. Kynard, unpub. data) and remain in shoals at dams (Buckley and Kynard 1985, O'Leary and Kynard 1986, Stone & Webster Env. Serv. 1991).

Schools of upriver migrants that swim from the open water into a fishway entrance must abruptly adjust the lateral and depth dimensions of the school. Fish on the periphery may be forced to leave the school, disoriented and alarmed. As size of the school becomes smaller during passage through the fishway, excitability and respiration rates of fish may increase. There may be selection against some behavioural or physiological phenotypes. There can be selection against large fish, thus indirectly against females as was found for alewives (*Alosa pseudoharengus*) (Libby 1981). Fishways that force fish to pass singly may have the greatest effect on schooling species.

Most upstream fishways contain mixed species of anadromous fishes. Some species, like American shad, attempt to maintain school integrity; others, like Atlantic salmon, move singly. The relative advantages and disadvantages for passage of each species probably change with fishway design, abiotic conditions, species present and relative numbers of each, relative minimum space used by individuals of each species, and social behaviour of species (solitary or schooling). Future study of schooling species and mixed species interactions in fishways could produce valuable new information for fishway design.

BEHAVIOURAL RESPONSE TO THE PHYSICAL ENVIRONMENT

Fish species have evolved the ability to discriminate between habitats, selecting only a certain space to occupy during migration. These choices ultimately contribute to the fitness of the individual. Fish often use proximate cues, particularly physical environmental factors, to select habitat.

In general, we have a poor understanding of the innate habitat preferences of eastern anadromous migrants to physical factors. This influences our ability to attract fish to fishways and to design fishways with the proper environment. The following section briefly discusses the behavioural responses of selected anadromous migrants to physical factors important for habitat selection.

ILLUMINATION

Migrants of some anadromous species respond strongly to natural illumination levels by displaying photopositive or photonegative behaviour. Adult alewives avoid intense mid-day illumination during migration (Richkus 1974) and avoid entering fishways on bright, sunny days (Lund *et al.* 1970). During sunny days, adult American shad avoid shade created by a low bridge (O'Leary and Kynard 1983). Juvenile migrant American shad and blueback herring select shade, not brightly illuminated habitat during mid-day (B. Kynard, unpub. data). Recent experiments with Atlantic salmon, Pacific salmonids, and shortnose sturgeon (*Acipenser brevirostrum*) found that phototactic responses can vary from species to species and with life stage (EPRI 1990, Richmond 1991).

Light intensity affects the rheotactic response and swimming behaviour of some fish. Pavlov *et al.* (1972) found that the minimum velocity in which fish will maintain position (critical velocity) is related to light intensity. This work predicts that as light intensity decreases below a threshold level at night, many fish should leave positions held in fast flows during the day and move to areas with slow flows. This conceptual model may explain the daily movement patterns of adult American shad and blueback herring seeking upstream passage below hydroelectric dams. American shad and blueback herring seek passage in high flow tailrace areas in the day, but move to slower flow areas downstream at night (Barry and Kynard 1986,

D. Cooke, pers. comm.). Preliminary results of experiments with migrant American shad at the Conte Anadromous Fish Research Center indicate many adult American shad select fast current habitat in the day and slow current habitat at night (E. Theiss and B. Kynard, unpub. data).

Movements of anadromous migrants have been directed by artificial illumination at hydroelectric dams and fishways for many years (Fields 1966), and these efforts continue (EPRI 1986, 1990). Atlantic salmon pre-smolts tested at night avoid strobe lights, but are not attracted to mercury light (EPRI 1990). Juvenile migrant American shad also avoid strobe light at night and this avoidance is the basis for development of a prototype bypass system at York Haven Dam on the Susquehanna River (Stone & Webster Env. Serv. 1991).

The optomotor response of some fish is controlled by endogenous (internal) daily rhythms (Schwassmann 1971). If the optomotor response of a species is endogenous, their ability to respond to illumination or darkness at improper times during the diel cycle will be affected. This could influence behaviour of fish at artificially illuminated or darkened fishway entrances or in illuminated or dark areas in the fishways themselves.

UNDERWATER SOUND

Water flowing through turbines, structures at dams, and fishways create low frequency underwater sound of less than 1,000 Hz. The literature indicates that fish detect only low frequency sound and are most sensitive to frequencies between 10-1,000 Hz (Hawkins 1986). Adult Atlantic salmon, the only eastern anadromous species yet studied in detail with respect to sound, are most sensitive to sound of about 160 Hz (Hawkins and Johnstone 1978). Clupeids have an elaborate hearing mechanism, but do not make sounds (Blaxter and Hunter 1982, Schwarz 1985). The biological significance of sound to these fishes is unknown. Any species using sound for orientation or communication may have problems in fishways because of the ambient levels of noise.

Avoidance of artificially generated low frequency underwater sound by fishes has only recently been investigated (review, EPRI 1986). The phenomena may explain the poor attraction to or performance in fishways of some species. Threadfin shad (*Dorosoma petenense*) avoid the low frequency sound in the intake area of Racine Dam created by the bulb turbine (WAPORA, Inc. 1987). *Oncorhynchus* spp. smolts avoid the sound created by guidance screens positioned in penstocks of hydroelectric dams, thus reducing the effectiveness of the fish protection devices (Hays 1988, Anderson 1988b).

Avoidance of high frequency (162 KHz) underwater sound by adult clupeids was discovered in the 1980s (O'Leary and Kynard 1983). This stimulus shows promise for guiding adult clupeids at fishways (Kynard and O'Leary 1990, Dunning *et al.* 1992, Nestler *et al.* 1992).

WATER MOVEMENT

Migrant behaviour is greatly affected by two characteristics of water movement: velocity and turbulence. Both factors influence the success of migrants in locating fishway entrances and passing through fishways. Changes in velocity alter the response of fish to any type of structure in the current, e.g., bar racks, louvers, or screens (EPRI 1986).

Upstream migrants often have difficulty passing through velocity barriers (i.e., areas where velocity changes abruptly from slow or moderate flow to fast flow). Velocity barriers, commonly found at upstream fishway entrances (Bell 1980) and culverts (Metsker 1970), may inhibit passage of adult American shad and other eastern anadromous species that do not jump.

Many diadromous species select the channel (area of maximum water velocity and maximum depth) when moving up- or downstream (Tesch 1979). This is the case with several eastern anadromous species such as adult American shad (Leggett 1976), juvenile American shad and blueback herring (B. Kynard, unpub. data), and Atlantic salmon smolts (Bakshtansky *et al.* 1982). Adults select reduced velocities in mid- to bottom depths, while juveniles select fast velocities near the surface (See section on Water Depth).

Preference for the route with the most flow by adult and juvenile migrants causes problems when they approach hydroelectric dams seeking passage. Greatest flows upstream from the dam often take migrants into turbines. Flows exiting the turbines into the tailrace below the dam often attract migrants more than the limited attraction flows from fishway entrances.

Radiotelemetry of Pacific salmonids and American shad below hydroelectric dams found a common result. Although many fish are attracted to the fast, turbulent outflow of the turbines in the tailrace, fish have difficulty locating fishway entrances in the turbulent water. Most fish enter fishway entrances located on the shorelines where flows are reduced, but more directional (Turner *et al.* 1984, Barry and Kynard 1985).

Water turbulence is detected by the lateral line system and causes orientation problems for fish. Fish may not get useful information about the current from turbulence (Arnold 1974). The wandering behaviour of migrants that encounter turbulence below a dam may be searching behaviour for sustained, directional flow. Attraction of fish to fishway entrances can best be done when migrants have directional water flow that leads to the entrance. Appropriate manipulation of turbine generation at hydroelectric dams can often create directional flow at entrances (Bell 1980). A partially submerged flume extending the fishway entrance along the shoreline downstream of turbulence might better attract fish.

WATER DEPTH

The vertical distribution of migrants can help determine the best location for fishway entrances and guidance devices. During the 1980s, hydroacoustic monitors were used at hydroelectric dams on the Columbia River to locate salmon smolts for protection from turbine passage. Smolts were usually in the upper part of the water column during migration (Raemhild *et al.* 1985). Atlantic salmon smolts also select the upper part of the water column (Ducharme 1972, Bakshtansky *et al.* 1982).

Studies with American shad and blueback herring found the following vertical distributions in the free-flowing river: adult American shad select the deepest one-third (Witherell and Kynard 1990); adult blueback herring select mid-water depths (Witherell 1988); and juvenile downstream migrants of both species select the upper 2 m (B. Kynard, unpub. data). The surface orientation of juvenile alosids suggest that a surface spill at some dams may effectively bypass these fishes.

ENTRAINED AIR

Fish often avoid air bubble curtains in the water column (EPRI 1986). Avoidance is strongest during the day when light reflects off the bubbles (Patrick *et al.* 1985). Although some adults of eastern anadromous species use fishways with large amounts of entrained air, the effects of entrained air on passage of fish needs investigation.

PHYSICAL STRUCTURES

Fish response to structure has been investigated in non-migratory fishes (Guthrie 1986). Physical characteristics of fishways involve the size, shape, dimensionality, brightness, color, and exterior design.

We know little about the response of migrants to structural features, but the available information indicates structure is important. Adult American shad avoid submerged orifices in fishways (Thompson and Gauley 1965, Rideout *et al.* 1985) and small fish avoid passing through bar racks at hydroelectric dams (Anderson 1988a). Both situations are examples where the structure/current velocity environment elicits a distinct response by fish: avoidance.

BEHAVIOURAL RESPONSE TO CHEMICALS

The acute sensitivity of adult salmonids to natal stream odors is the basis of homing by salmonids (Stabell 1984, Hara 1986) and, possibly, by alosids (Thunberg 1971, Atema *et al.* 1973, Dodson and Leggett 1974, Dodson and Dohse 1984). Chemical odors can stimulate rheotactic movements of fish (Tesch 1979).

Although the chemical sensitivity of anadromous migrants is well established, chemicals have not been used to enhance passage of fish. Brett and Alderdice (1958) used odors with mixed success to attract salmonid smolts for downstream passage. Chemicals are not presently being used to attract or repel migrants for passage. The cost of the large volumes of chemicals needed may have discouraged research with chemicals for fish passage.

BEHAVIOUR AND THE BIOLOGICAL ENVIRONMENT

Migrants moving upstream through fishways compete for a limited resource: space. Bell (1980) suggests that species interactions in fishways could result in excessive activity, fish drop-back, or damage to fish attempting to exit. There are guidelines for the amount of space needed for fish in fishways and fish lifts (Bell 1980). The recommendations apply irrespective of fish species and seek to maintain adequate water quality for fish life. Space guidelines that account for behaviour of fish are not available.

There is often concern about competition for space in fishways between desirable and less-desirable species (e.g., competition between adults of American shad and sea lamprey). A productive approach has been to find behavioural differences that separate the two species in the fishway. Sea lampreys are excluded from moving upstream with salmonids in a fishway using behavioural differences in jumping ability (Wisconsin DNR 1990).

The behaviour of some species may influence use of a fishway by other species. The presence of many adult anadromous sea lampreys (70 cm average length) attached to walls and dangling over weir crests makes the openings smaller, changes the flow regime, and may deter some fish from passing.

Predation of eastern downstream migrants does not yet appear important as a factor influencing the use of fishways. This may change as predators adapt to the new passage situations. Predation could be important for upriver passage of small adults if large predators, e.g., walleye (*Stizostedion vitreum vitreum*), establish residency in fishway pools and prey on and disrupt upstream movement of migrants.

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BEHAVIOUR OF ADULT AND JUVENILE AMERICAN SHAD (*Alosa sapidissima*) MOVING TOWARD A POWER STATION

by

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ABSTRACT

During the past three years, studies were conducted during the downstream migration of adult and juvenile American shad to assess their behaviour while moving toward Hydro-Quebec's Rivière-des-Prairies power station. Much of the information was obtained using hydroacoustic and radiotracking techniques. In the forebay, adult distribution was related to flow. Their abundance increased as they approached the facility. Adult shad explored the facility for an average of 19 hours, after which time they continued their downstream migration. Shutting down the power station and opening the spillway allowed the passage of 75% of these fish.

Juveniles tended to form dense schools very close to turbine intakes (<5 m). Their distribution in the water column was strongly influenced by daylight which in turn influenced their entrainment through the turbines. Attempts to repel the fish with a sonic deterrent gave unsatisfactory results under normal conditions at the Riviere-des-Prairies site. The short range of the deterrent, and the fact that fish became accustomed to it, does not make this a practical solution to entrainment.

INTRODUCTION

Entrainment of fish at hydroelectric facilities and mortality associated with passage through turbines are of increasing concern to fisheries biologists and electric utilities. This problem is especially critical for species that must migrate past powerhouses in order to complete their life cycle. Returning spawners or their progeny may suffer from turbine-related injuries or mortality following spawning. Because of their life cycle, salmon and American shad are particularly susceptible to this type of stress.

Several studies have been initiated in the United States, Canada and Europe to evaluate the possible causes of fish mortality in hydroelectric turbines and to find means of diverting fish away from intakes. Ruggles and Collins (1981), Montén (1985), and Larinier and Dartiguelongue (1989) provide a good review of the subject of turbine-related fish mortality, while Stone & Webster (1986) make a thorough review and assessment of available protection techniques for migrant fish.

It is necessary to have a good understanding of fish behaviour if one is to guide fish toward bypasses. Migratory instinct is strong and any guidance device is more likely to work properly, at lower cost; if designed in accordance with fish behaviour. .

The des Prairies River, which flows north of Montreal Island, is used by American shad (*Alosa sapidissima*) during their upstream and downstream migration. Adult and juvenile shad encounter the Riviere-des-Prairies power station on their route toward the sea. The behaviour of adult shad during their upstream migration is well documented in studies on the Connecticut River (Leggett and Jones 1971, Dodson *et al.* 1972, Dodson and Leggett 1973, 1974, Leggett 1976, Kynard 1982), and on the Susquehanna River (RMC 1987, 1988, 1989). On the other hand, the behaviour of outmigrating shad has only recently received attention. Witherell and Kynard (1990) studied the vertical distribution of emigrating adult shad, while Loesch *et al.* (1982), and O'Leary and Kynard (1983, 1986) studied the behaviour of seaward migrating juvenile American shad in the Connecticut River. The movements of juvenile shad in the forebays of Susquehanna River hydroelectric facilities and their reaction to sound and light deterrents were recently examined (Barnes-Williams and St. Pierre 1987, Metropolitan Edison Co. and EPRI 1988, Stone & Webster 1990).

During the past three years, studies have been conducted during the downstream migration of adult and juvenile American shad to assess their behaviour while moving toward the Riviere-des-Prairies power station. This paper describes the principal findings.

DESCRIPTION OF STUDY SITE

The Riviere-des-Prairies power station is located on the des Prairies River, between the islands of Montreal and Laval, Québec. Built in 1928-29, the power station consists mainly of a powerhouse located on the left side of the river and an adjacent spillway with 13 vertical gates (Figure 1). This is a run-of-river facility, and all the flow that does not pass through the powerhouse must be spilt. The average flow of the river is 1080 m^3/s, but during the freshet can often reach 2000 m^3/s. While the turbine capacity is 855 m^3/s, the turbine flow rarely exceeds 700 m^3/s. Given these conditions, the spill flow, although variable, may be large and sometimes exceeds the turbine flow.

The powerhouse has six generating units, each supplied by three inlets; each inlet is 5 m wide and 8 m high, with water being drawn from a depth of 2 to 10 m. The spillway has thirteen vertical gates, and under normal operating conditions, spillage is distributed over several gates causing fish to sound 7 m before leaving the forebay.

METHODS

ADULTS

Most of the adults outmigrate during the first three weeks of June. Figure 2 depicts the prevailing flow conditions from June 6 to 27 1989 and 1990. In 1989, because of the breakdown of a main transformer at the powerhouse, the turbine flow was kept at 250 m^3/s, while the spillage varied between 1000 and 1500 m^3/s. In 1990, the turbine flow varied between 550 and 650 m^3/s, while the spill flow was between 200 and 550 m^3/s.

In 1989, the relative size of spillage allowed a major proportion of the adult population to emigrate under the spillway gates. When the gates are 1 m open, the passage of the shad can be easily observed and visual counts during daytime can yield precise estimates. Between June 13 and 29, 5 minute counts were made hourly to study the migration rhythm. A total of 51 counts were made, between 8:00 a.m. and 5:00 p.m. Circadian movements in the forebay were studied using hydroacoustic techniques. A Biosonics transducer mounted in front of gates 2 and 3 allowed evaluation of shad density at that location.

In 1990, adult behaviour was studied in the forebay using hydroacoustic and radiotracking techniques. Hydroacoustic transects were made 35 m apart in front of the powerhouse and the spillway from June 11 to 27, at different times of day (Figure 1). Hydroacoustic transects were made with the transducers mounted vertically looking toward the river bottom. A total of 43 passes were made on transect No. 1, 26 on transect No. 2, 25 on transect No. 3, 24 on transect No. 4 and 22 on transect No. 5.

On June 12, during the migration peak, an attempt was made to attract shad to the spillway by flow manipulation. At 5:00 p.m., the powerhouse was shut down except for a residual flow of 44 m^3/s while the turbine flow was transferred to the spillway. The turbine flow dropped from 645 to 44 m^3/s while the spill flow increased from 259 to 962 m^3/s. Between 5:00 and 6:00 p.m., the spill flow was distributed through 7 gates. From 6:00 to 7:00 p.m., the spill flow was concentrated on gates 1 and 2. After 7:00 p.m., the operating conditions gradually returned to normal. Behaviour patterns of the fish during and after these procedures were followed by hydroacoustic passes on transect No 1.

Individual movements in the forebay were monitored using radio transmitters. Between June 16 and 21, 33 individuals were captured approximately 18 km upstream of the power station. Radio transmitters were inserted in their stomachs, and the fish were released immediately on the site, to minimize stress and erratic behaviour. Fish movements were monitored by automatic recording receivers as they approached the hydroelectric facilities. Signals were received through two master antennae connected to six auxiliary antennae on the powerhouse walkways, a similar antenna array was installed on the spillway. The master antennae detected the presence of a marked fish in the forebay, while the auxiliary antennae located fish with greater accuracy.

JUVENILE

Juvenile shad emigration in des Prairies River takes place between mid-July and mid-September, with peak migration typically occurring at the end of July and beginning of August. Entrainment at the powerhouse was studied by making visual observations of gulls and capturing fish with hoop nets. On June 27 and 28, 1988, during the peak of juvenile migration, a 1 m diameter hoop net was used in the tailwater, attached to the powerhouse by a 48 m long cable. Fifteen minute samples were taken each hour over a 24 hour period to provide information concerning the circadian rhythm of entrainment. This activity was completed by diurnal counts of gulls and gull dives in the tailwater. When outmigrating, juvenile shad are easy prey for gulls below the powerhouse. The .average number of gulls and gull dives over a two minute period was noted hourly; these observations were correlated with results from the hoop nets. In the forebay, juvenile behaviour was studied by hydroacoustic transects in front of the powerhouse and the spillway gates between July 25 and August 1990.

In 1989, a sonic deterrent was tested during the juvenile migration. The device, marketed by FMC under the name Fishpulser, consists of an 80 cm diameter, 1 m long metal cylinder with a steel plate at one end and a hammer mounted inside the cylinder. When the hammer hits the end plate, a low-frequency sound is emitted in the water. The juveniles were attracted to the spillway since most of the flow passed through the spillway. Therefore, the pulser was then immersed a few metres in front of one of the spillway gates, first at a depth of 0.5 m and then at 1.5 m, with a slight inclination towards the river bottom. Fish movements in front of the pulser were monitored using hydroacoustic equipment. Figure 3 illustrates the fish pulser and transducer position in front of a spillway gate.

RESULTS AND DISCUSSION

ADULTS

In 1989, there was irregular passage of adult shad through the spillway. Before 2:00 p.m., an average of fewer than 10 individuals passed each gate per five minute period (Figure 4). At 3:00 p.m. the counts increased to 20, reaching a maximum of 32 at 4:00 p.m., after which counts decreased. Hydroacoustic observations made in front of the spillway provided complementary information on adult emigration rates. Average target abundance was very low between 9:30 p.m. and 5:00 a.m. (Figure 5). From early morning until late afternoon, concentrations of fish increased in front of the spillway until they peaked between 3:00 and 6:30 p.m., after which the abundances decreased. Combining the two types of information led to the hypothesis that downstream passage under the spillway gates was related to diurnal vertical fish movements or increased lighting of the openings. Although fish were abundant in front of the spillway gates during early afternoon, they usually passed under the spillway gates late in the afternoon. The situation may have been different at the turbine intakes, which cover a larger portion of the water column.

Hydroacoustic transects in front of the facility provided information about fish distribution relative to flow. Figure 6 shows fish distribution along transect No.l, in front of the powerhouse on June 14 at 11:00 a.m.; while Figure 7 illustrates fish distribution along transect No.l in front of the spillway at the same time. Individuals were more numerous in front of the powerhouse than in front of the spillway, where flow represented only 27% of total flow. High concentrations of fish were found in front of the intakes of turbines 3 to 6, at depths of 2 to 10 m. Fewer animals were found in front of the spillway, along gates that were completely closed. Only gates 1 and 13 were partially open, and many targets could be observed from gates 2 to 9, which were fully closed. These results suggest that fish were attracted by turbine flow. However, the great number of fish beside the main outflow suggests they are actively looking for alternative routes.

Figures 8 and 9 provide relative abundances of hydroacoustic targets along five transects made in front of the powerhouse and spillway, during the emigration period. Clearly fish abundance increased as they approached the facilities. Targets were very abundant on transect 1, a few metres in front of the facilities, but were very sparse along transect 5, 135 m away. It appears that fish did not readily pass through the facilities, but instead accumulated in front of the powerhouse, and, to a lesser extent, the spillway. Comparisons between Figures 8 and 9 clearly demonstrates that fish tended to accumulate in front of the powerhouse rather than the spillway. This is not surprising since the highest flow rates were in front of the turbines. Figure 10 illustrates the relationship between the relative amount of spilt water and the relative abundance of fish as determined by the hydroacoustic targets. Abundances of shad in front of the spillway gates increased as the amount of spilt water increased. On June 19 spillage reached 40% of total flow. At this time, about 40% of the fish targets were observed in front of the spillway. Thus, flow appears to be the main emigration route attractant.

Figure 11 depicts fish abundance in front of the powerhouse and spillway before, during, and after powerhouse shutdown on June 12. Just before the shutdown, about 75% of the fish were in front of the powerhouse and 25% in front of the spillway. Between 5:00 and 6:00 p.m., the powerhouse was shut down and flow was distributed through 7 of the spillway gates. The fish swam in front of the spillway gates because of attraction to the increased flows. By 6:00 p.m. more than 90% of the fish had moved to the spillway. Between 6:00 and 7:00 p.m., after the flow had been concentrated through gates No.l and 2, the fish emigrated massively; more than

75% of the fish left via the spillway. After 7:30 p.m., when the powerhouse was put back in operation, the number of fish began to concentrate in front of it. Between 8:00 and 8:30 p.m. there was a slight increase in the forebay after which the abundance remained relatively constant and then increased again early in the morning.

Of the 33 adult shad that were radiotagged upstream of the power station, 14 were recorded at the facility. Those exhibiting movements associated with a dead or dying fish were discarded, leaving 8 fish with active behaviour patterns. These fish took an average of 2.5 days to cover the 18 km between the tagging site and the facility. Five fish explored the powerhouse and the spillway, while three explored only the powerhouse. On average these adult shad remained in the forebay for 19 hours. This period was, however, highly variable ranging from 50 minutes to more than 90 hours for the 8 individuals considered. Those which explored only the powerhouse remained in the forebay for a shorter time (<4 hours) than those which explored the powerhouse and the spillway (between 6 and 91 hours).

All the fish exhibited active exploration behaviour. Those in front of the powerhouse were recorded more often in front of the turbines which were in operation, especially turbines 4 and 5. Figure 12 shows two examples of exploration behaviour. In the first, the fish arrived at 5:30 p.m. It explored the powerhouse for 21 minutes before swimming to the spillway. At 6:44 p.m. it returned to the powerhouse, explored the turbine intakes for almost two hours and then was entrained. In the second example, the fish arrived at 4:31 a.m. After exploring the main outflow for 50 minutes, it moved downstream through the powerhouse.

Hydroacoustic results, along with data gathered from radiotagged fish, show that fish hesitate in front of the power station before moving downstream. They actively explore the facilities, and as a result, there is a build up of fish close to the powerhouse and, to a lesser extent, in front of the spillway. The powerhouse, and possibly also the spillway, represent an obstacle to downstream migrations. Many characteristics of the powerhouse may scare the fish: principally darkness, noise, vibration, and flow acceleration.

Leggett and Jones (1971) concluded that sight plays an important role in the upstream migration of adult shad. It is likely that vision is also important to emigrating shad. The powerhouse and spillway structures may act as visual barriers to migrating adults and temporarily delay their seaward migration. They also concluded that other senses, perhaps lateral line, may play a role in obstacle detection. Turbine revolutions cause significant noise and vibrations which are felt by fish, since they easily detect low frequency sound.

Very few studies cover the behaviour of adult shad approaching a power station. On the Susquehanna River, tagged emigrating shad moved quickly past Safe Harbor and Holtwood dams. No shad utilized either forebay for more than six days (RMC 1988). The amount of water discharged over Holtwood Dam appears to determine the extent to which shad move into and/or remain in the spillway area (RMC 1989).

JUVENILES

The rate of juvenile entrainment in turbine inflows is not constant during the day. Results from gull counts and hoop net catches indicate a high level of entrainment during the morning (Figure 13). Peak movement occurs between 8:00 and 9:00 a.m., after which there is a significant decrease in number, with less entrainment, until 5:00 p.m. when a slight increase is observed. Hoop net fishing did not reveal noticeable entrainment during the nighttime. Movement resumed after sunrise, at 7:00 a.m.

Hydroacoustic surveys in front of the turbine intakes offer an explanation of the phenomenon involved in juvenile entrainment. During the evening, fish moved toward the surface where the water velocity was low. With increasing daylight, the fish began to sound deeper in the water column. Once they reached a depth of 2 to 3 m and approached the turbine intakes they probably could not resist the currents for long periods of time and became entrained into the powerhouse. Figure 14 illustrates fish distribution along transect No. 1 on August 9 during peak migration at 10:00 a.m. At this time, several fish were found within 2 m of the surface, whereas, fewer fish were found below 3 m where water velocities were higher.

Fish were usually detected within a few metres of the powerhouse. On rare occasions schools were noticed more than 10 m away. In 1990, most of the flow was discharged at the powerhouse, and only a few schools were detected in front of the spillway.

Flow rates had a greater influence upon juveniles than adults. Juveniles remained closer to operating turbines than adults. Schools were rarely seen away from inflows. Juveniles exhibited daily vertical movements that were associated with darkness avoidance. Observations in powerhouse gate wells provided further evidence of this phenomenon. Gate wells covered with lids were usually deserted by juveniles, however, young shad quickly returned once the lids were removed.

The use of an acoustic deterrent did not induce a very strong response on the part of the juveniles. Fish reacted by moving about 1.5 m closer to the water surface (Figure 15). When the pulser was not in use, fish usually swam at a depth of 2.5 and 4.5 m. When the device was activated, the fish swam in the upper 3 m. The effective range of the deterrent was short; fish swam within a few metres in front or behind it. Experiments with the pulser in a gate well showed that after 3 min. the fish became accustomed to the sound Consequently, no reaction was observed on underwater video cameras.

Downstream migration of juvenile shad is better documented than for adults. Loesch *et al.* (1982) have already shown that a vertical movement is associated with light intensity. Surface pushnet catches were significantly greater at night than during the day. More recently, hydroacoustic studies were conducted to examine the behaviour of juvenile shad approaching hydroelectric stations on the Susquehanna River. In the York Haven station, shad targets entering the forebay were concentrated in an area with a water velocity of approximately 0.5 m/s. Their movement was always downstream toward the powerhouse (Barnes-Williams and St. Pierre 1987).

Studies conducted at the Holtwood hydroelectric station also suggest that juvenile shad movement is strongly related to flow. When spillage was increased, juveniles were not able to detect flows into the powerhouse and were attracted to the spillway (Acres 1989). Monitoring of radiotagged fish at this facility indicated that a log chute was not often used by emigrants and therefore does not provide great potential as a bypass.

In experiments with salmonids, sound producing devices looked promising for guiding young salmonids (Patrick and McKinley 1987). However, under the conditions prevailing at the Rivière-des-Prairies site, they are not efficient enough to be used on a large scale. Experiments made on the Susquehanna River led to the same conclusion. These results suggest that the aggregation of fish in front of the units exhibit a startle response and avoid some of the projected sound. However, the avoidance responses were not strong and did not displace fish a great distance from the source. Furthermore, the displacements were not sustained. The fish rapidly acclimated to the condition and returned to the study area (Metropolitan Edison and EPRI 1988).

CONCLUSIONS

The majority of seaward migrating adult shad were attracted to the high flows in front of operating turbines. They were not readily entrained. In fact some explored the outlets for several days. As a result, their abundance increased in front of the structures. Before an efficient means of guiding adults to a safe bypass is found, shutting down the powerhouse, with flow diversion toward one or two spillway gates for a short period of time represents an efficient means of allowing emigrating adults to bypass powerhouses. Regardless of the type of guidance barrier used, bypasses should have good attraction flows.

Very few schools of juvenile shad were far from the operating turbine. Like adults, they are not readily entrained. Their densities peaked within 10 m of the powerhouse and circadian entrainment was related to diel vertical movements. As shad swam down through the water column they encountered fast-moving water that they could not swim against.

Sound deterrents did not represent a practical solution to entrainment at large hydroelectric stations because of their short effective range and the fact that fish became accustomed to them.

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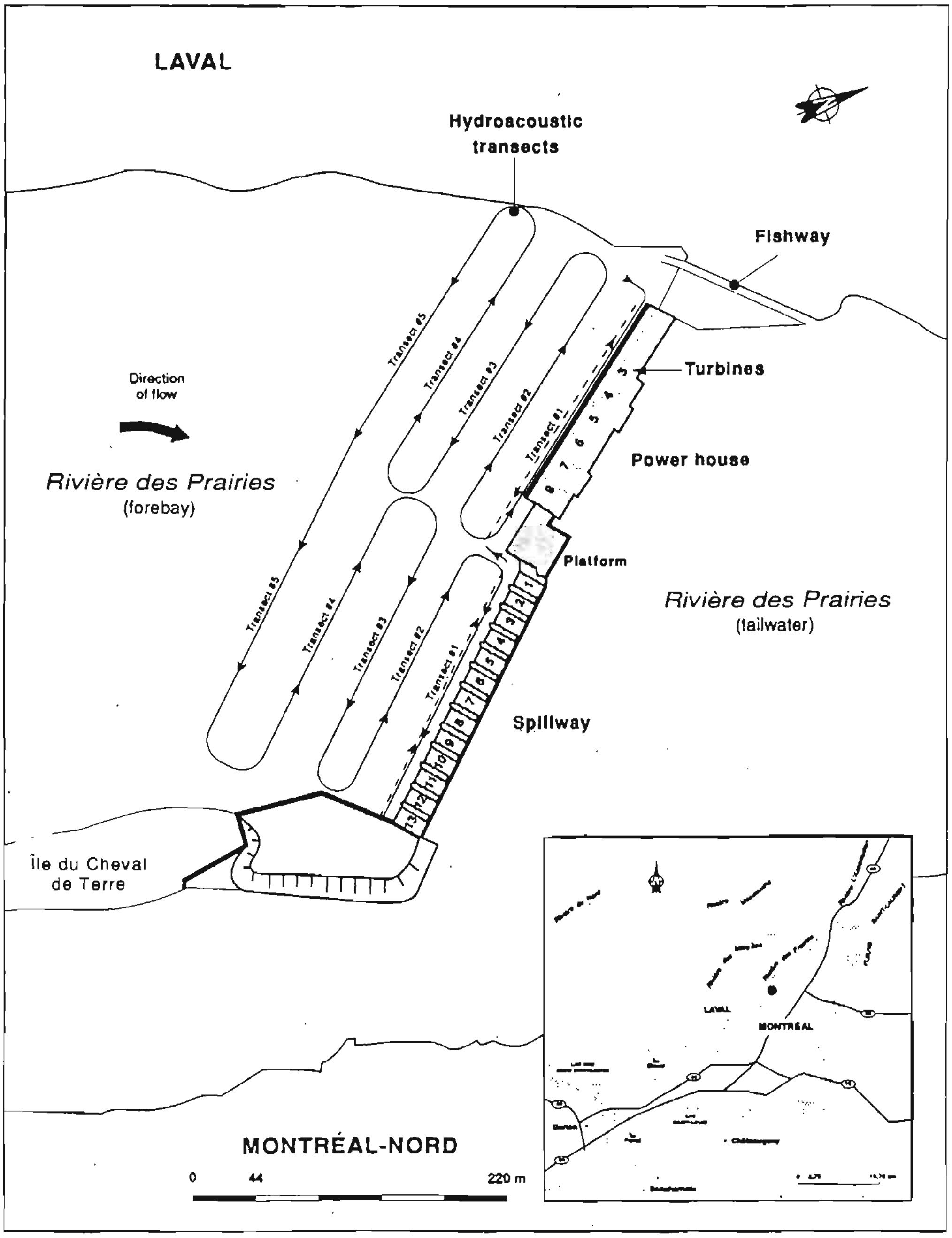

Figure 1. Locations of hydroacoustic transects at the Rivière-des-Prairies hydroelectric facility.

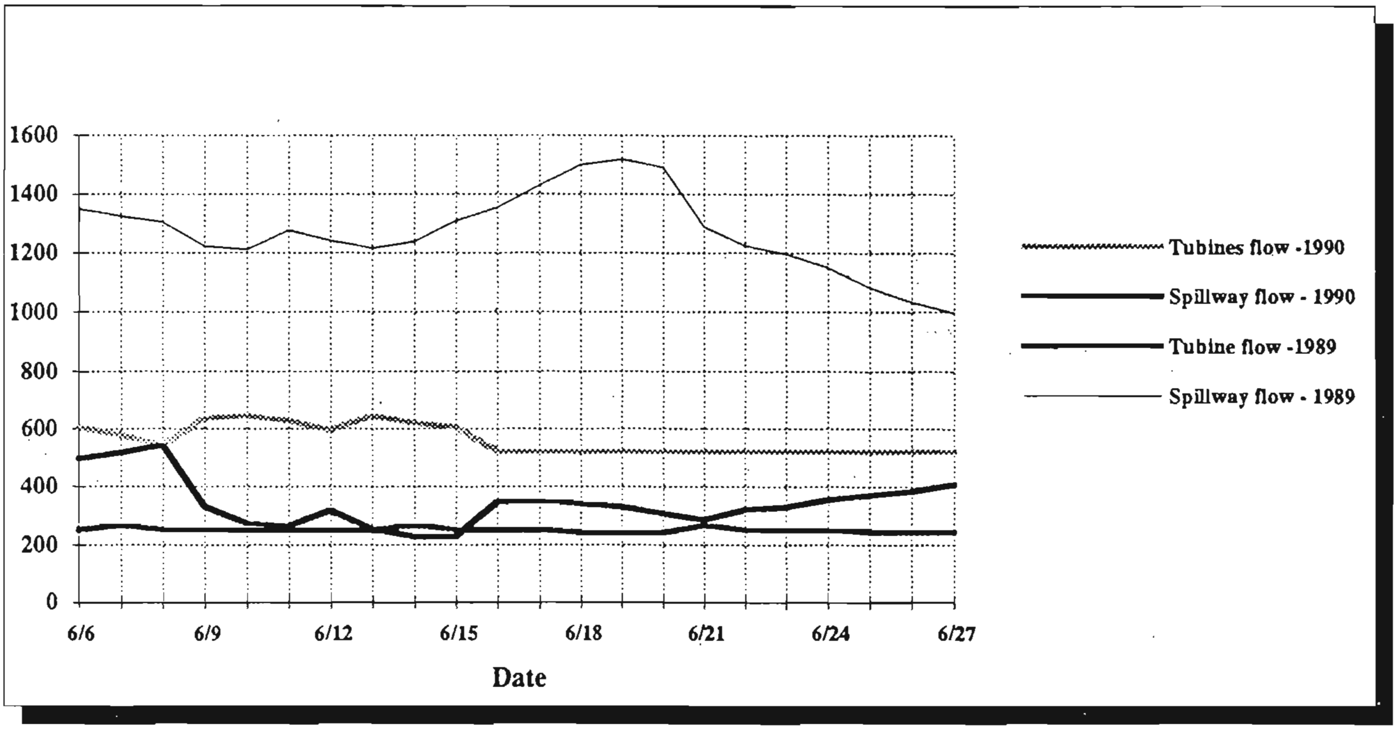

Figure 2. Average daily flow (m^3/s) at the powerhouse and spillway.

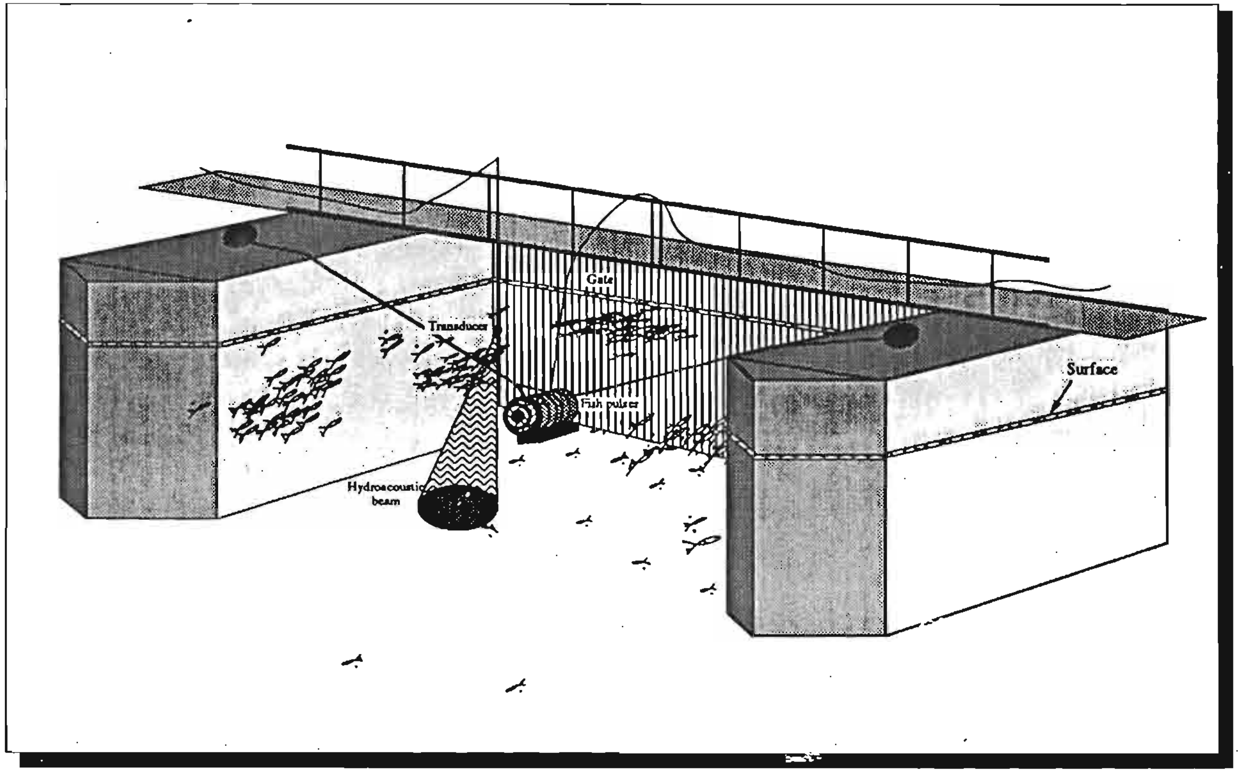

Figure 3. Acoustic deterrent and hydroacoustic transducer in front of a spillway gate.

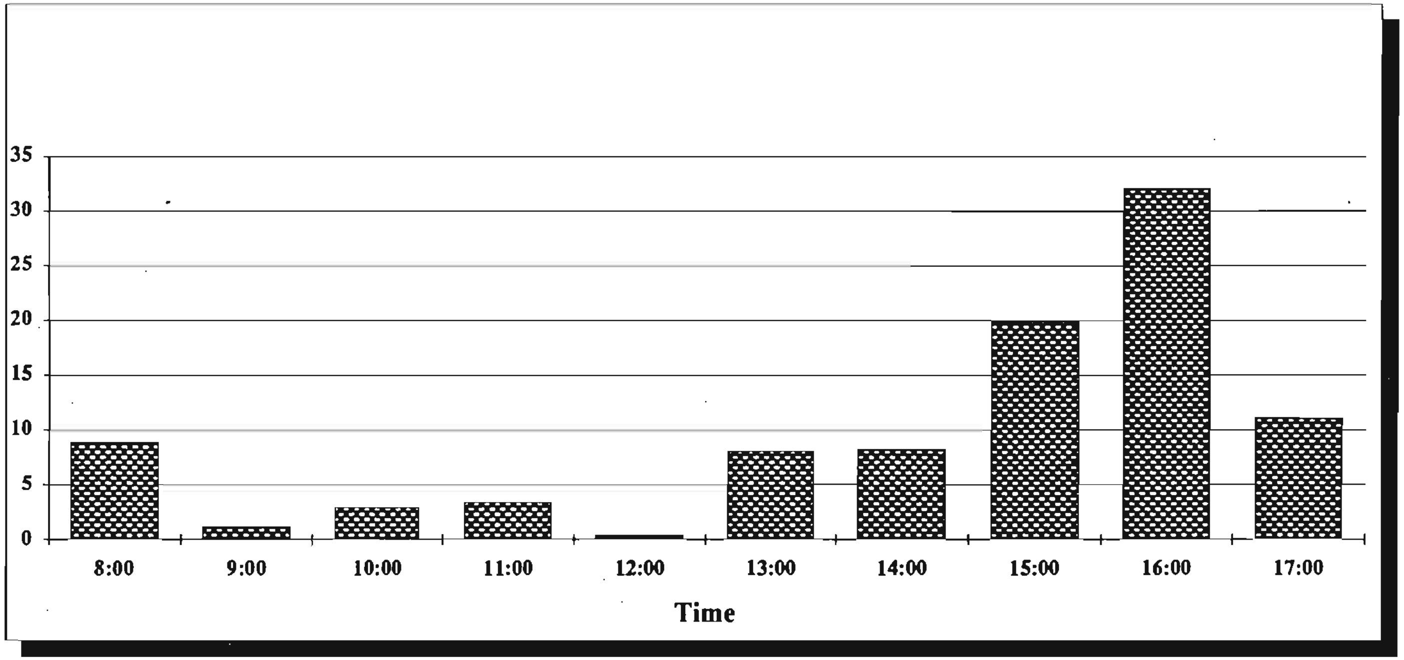

Figure 4. Downstream migration at spillway during daytime. (Average number of shad per 5 min count period)

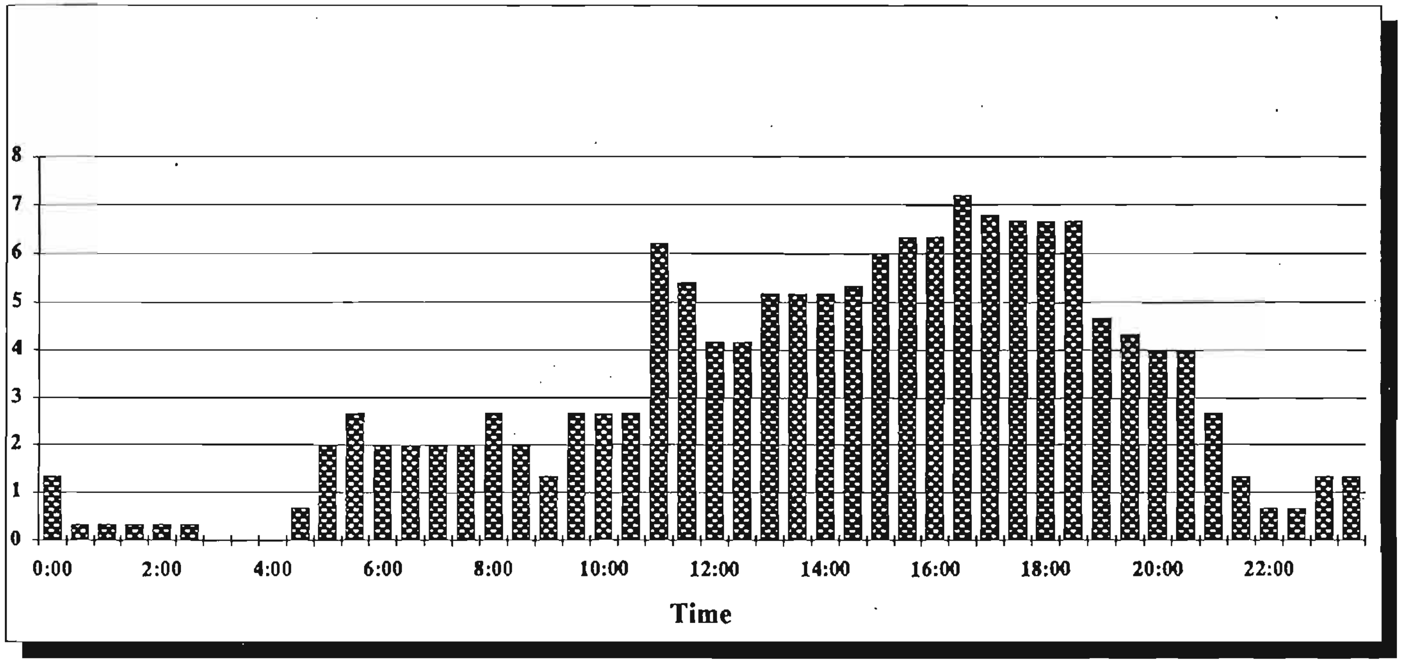

Figure 5. Diel distribution of fish at spillway. (Average target abundance)

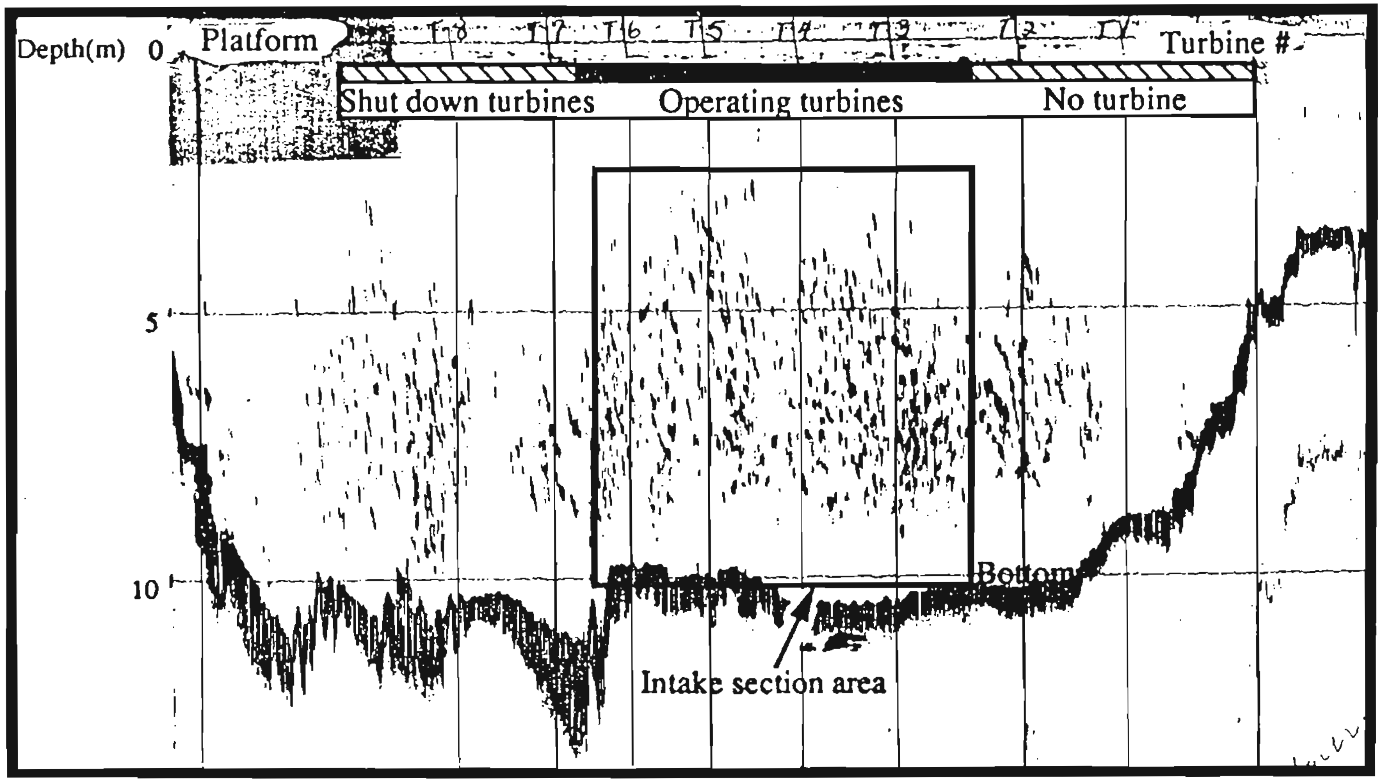

Figure 6. Hydroacoustic transect # 1 (June 14, 1990) at 11:00 a.m., close to the powerhouse (3m).

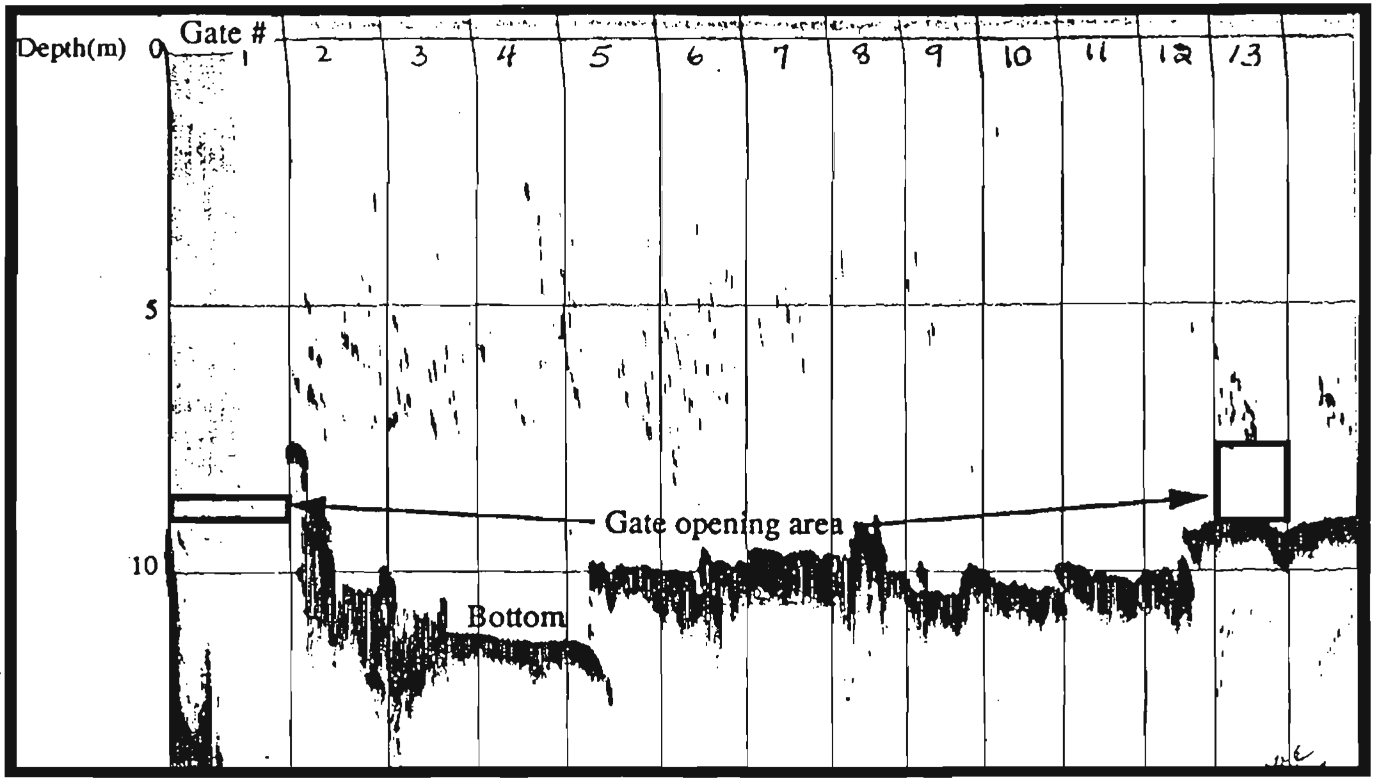

Figure 7. Hydroacoustic transect # 1 (June 14, 1990) at 11:00 a.m., close to the spillway (2m).

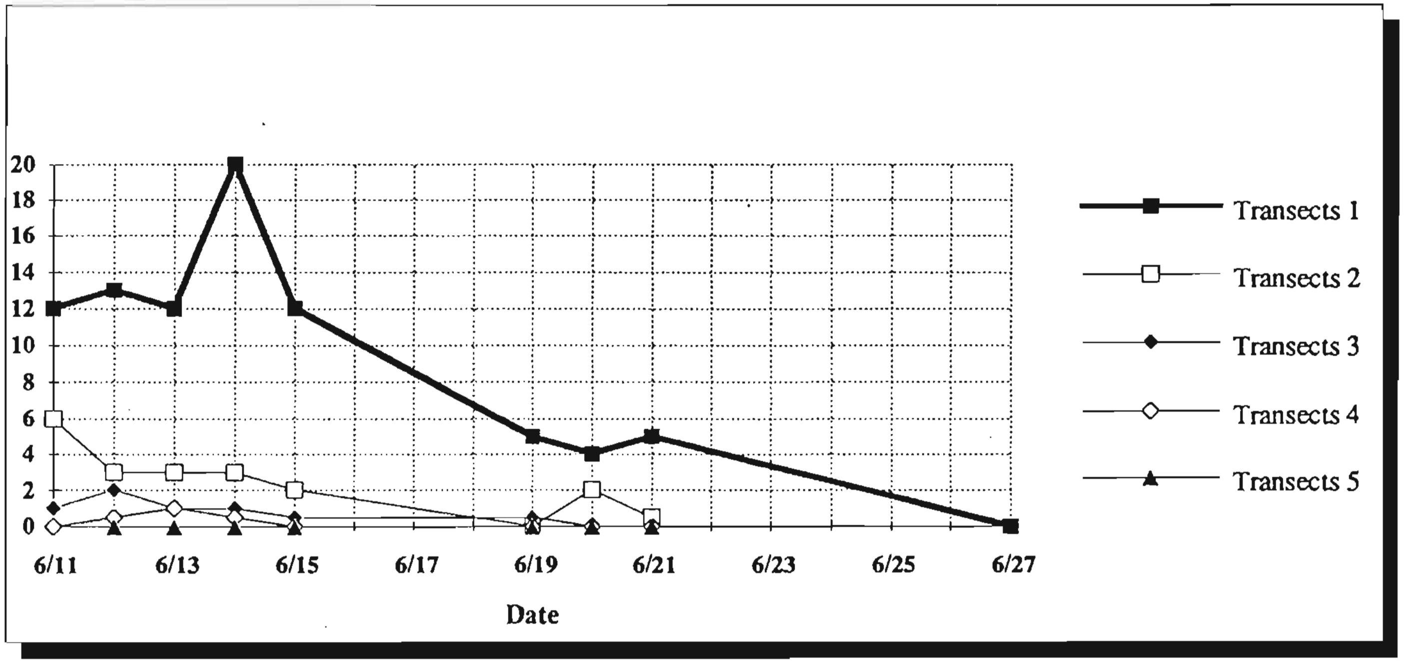

Figure 8. Relative abundance of hydroacoustic targets in front of the powerhouse at 11:00 a.m. from June 11 to 27, 1990.

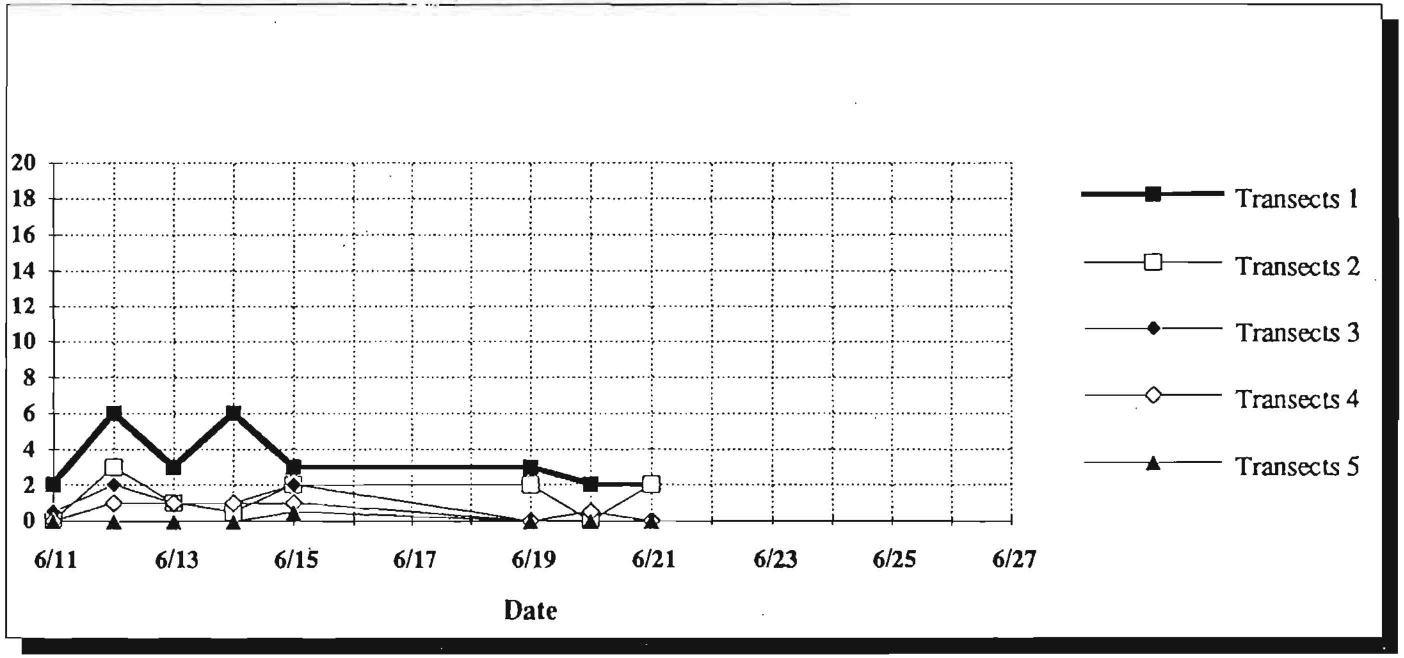

Figure 9. Relative abundance of hydroacoustic targets in front of the spillway at 11:00 a.m. from June 11 to 21, 1990.

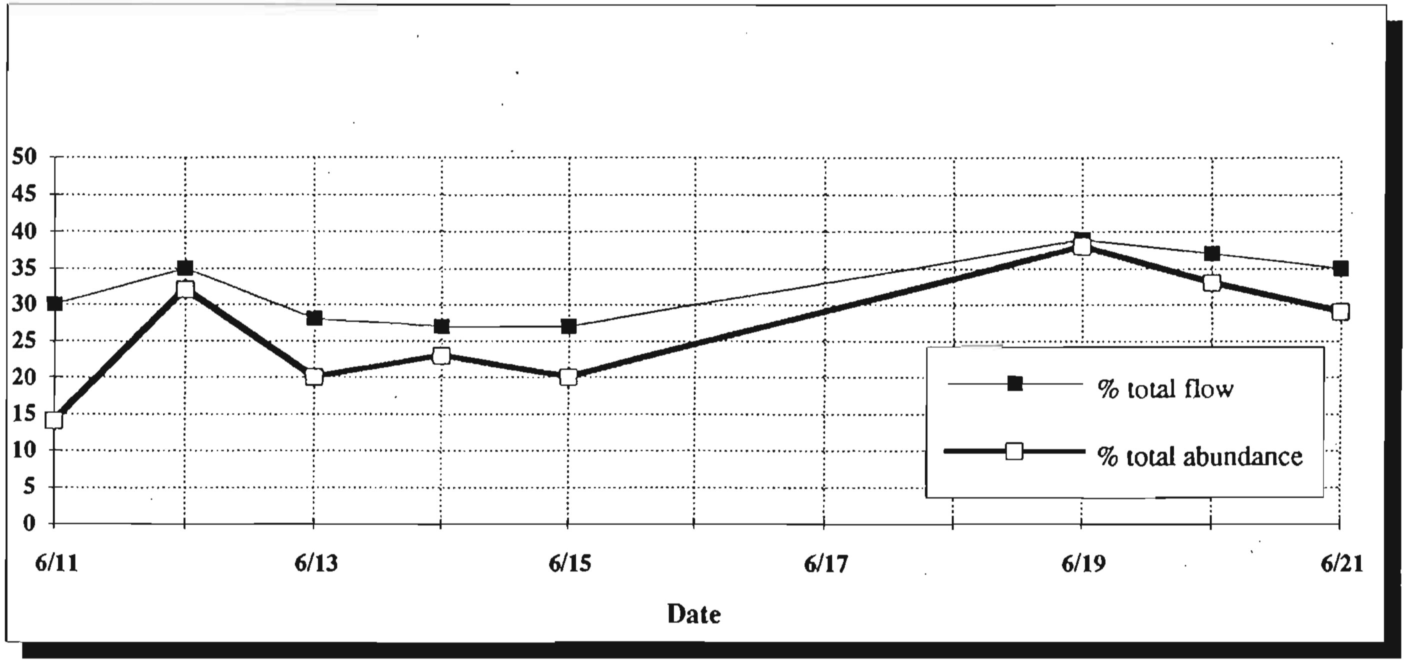

Figure 10. Relation between spilt water and shad abundance at the spillway. Percentage of total flow and total abundance along transect # 1.

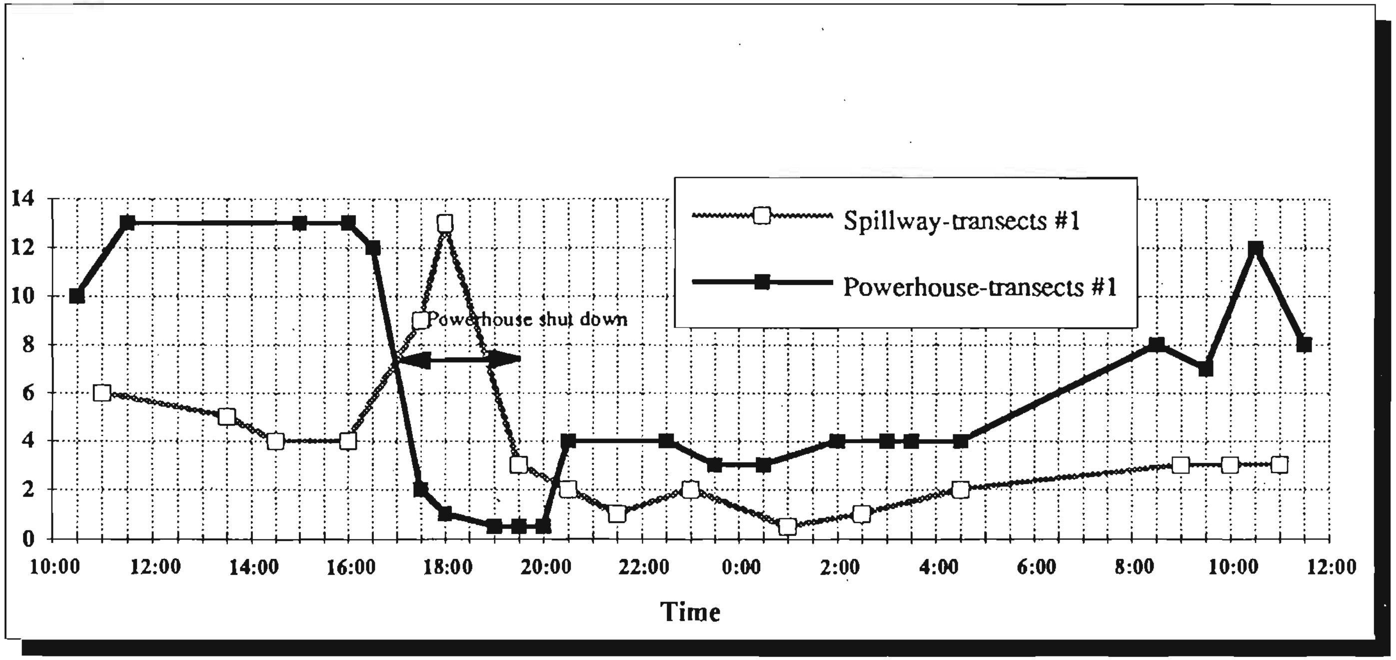

Figure 11. Attraction experiment at the spillway. Relative abundance of hydroacoustic targets between June 12 (10:30 a.m.) and June 13 (11:30 a.m.).

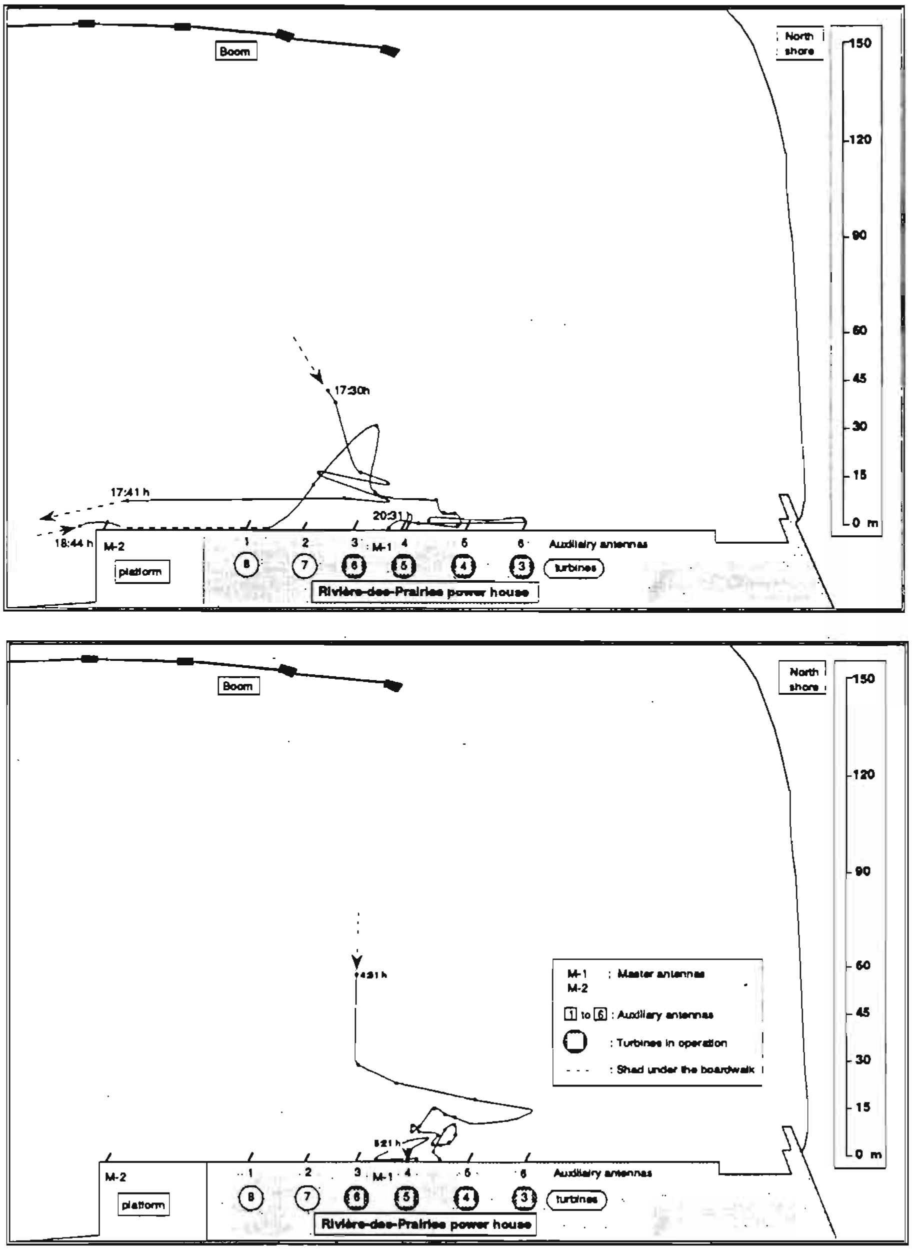

Figure 12. Example of exploration behaviours by two adult shad.

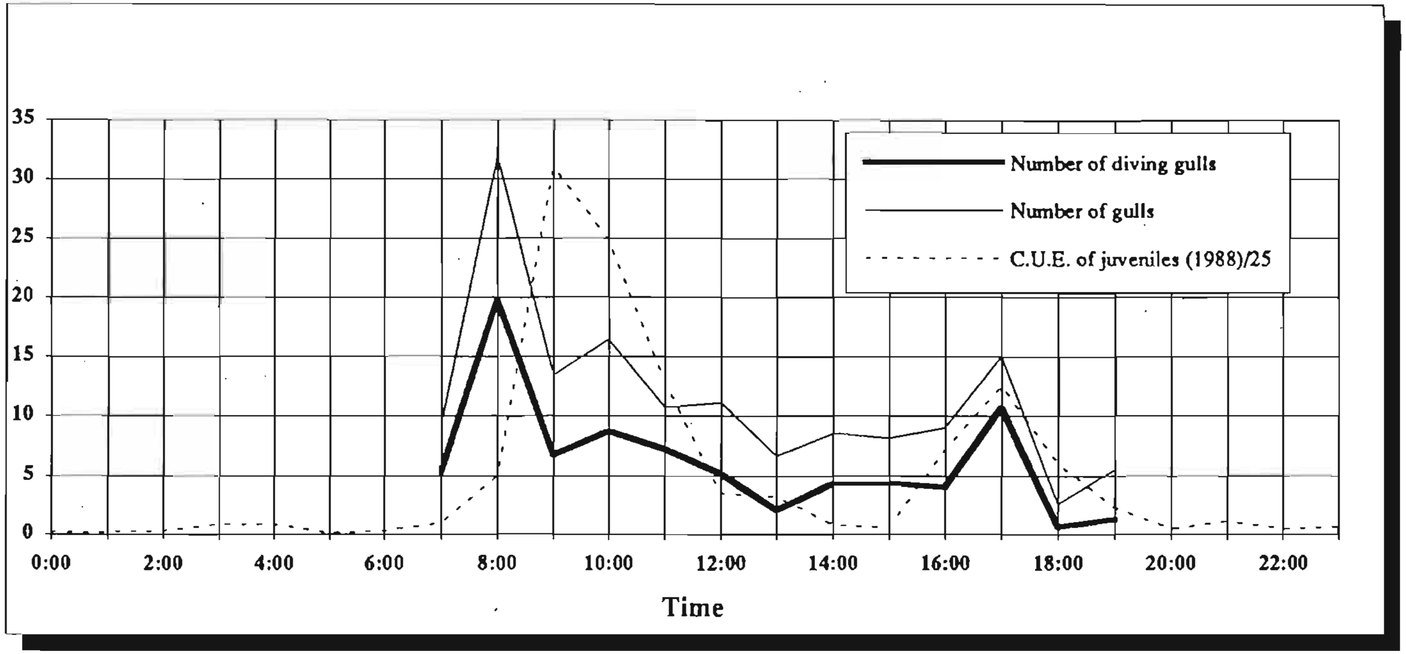

Figure 13. Entrainment of juvenile shad at the power house.

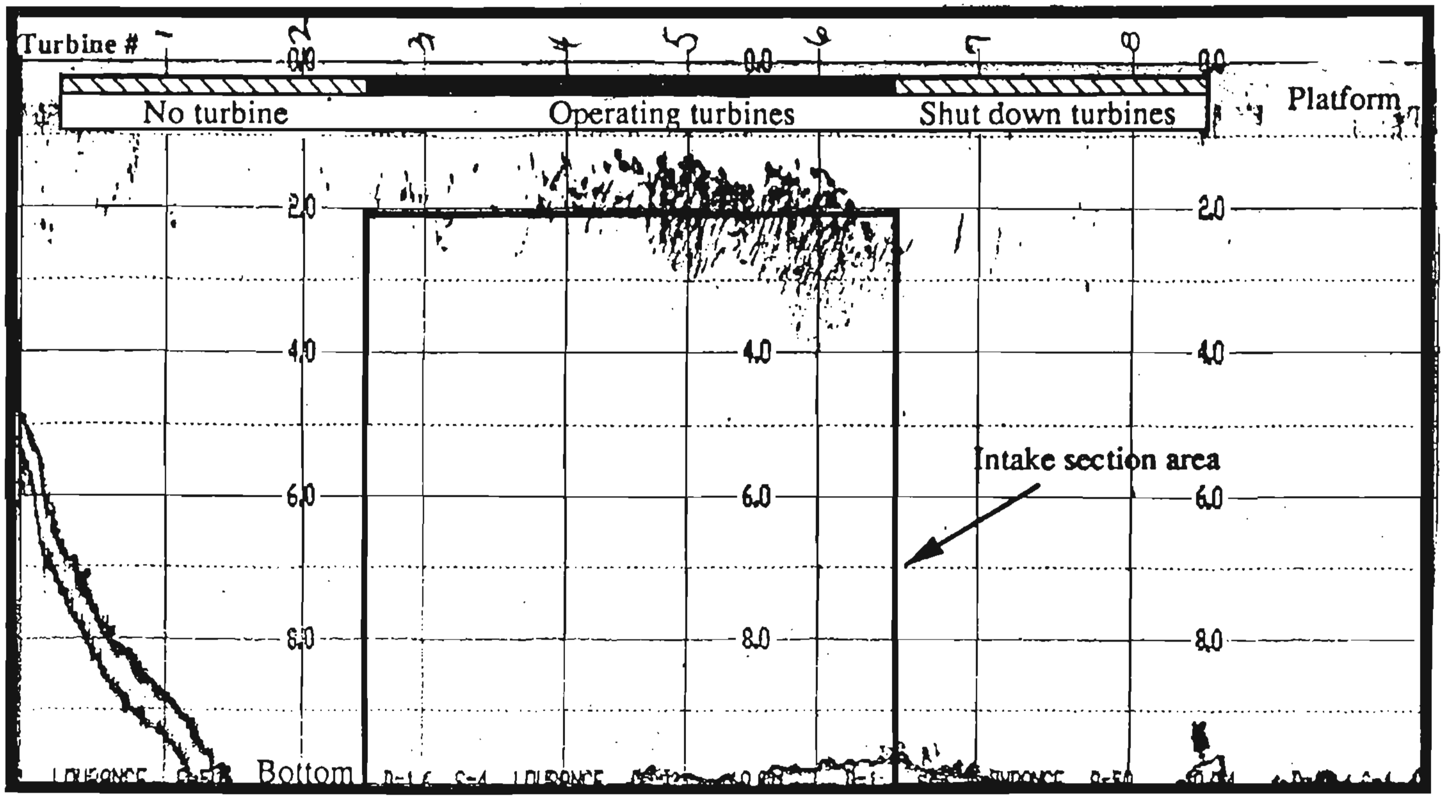

Figure 14. Hydroacoustic transect # 1 (August 9, 1990) at 10:00 a.m., close to the powerhouse (3m).

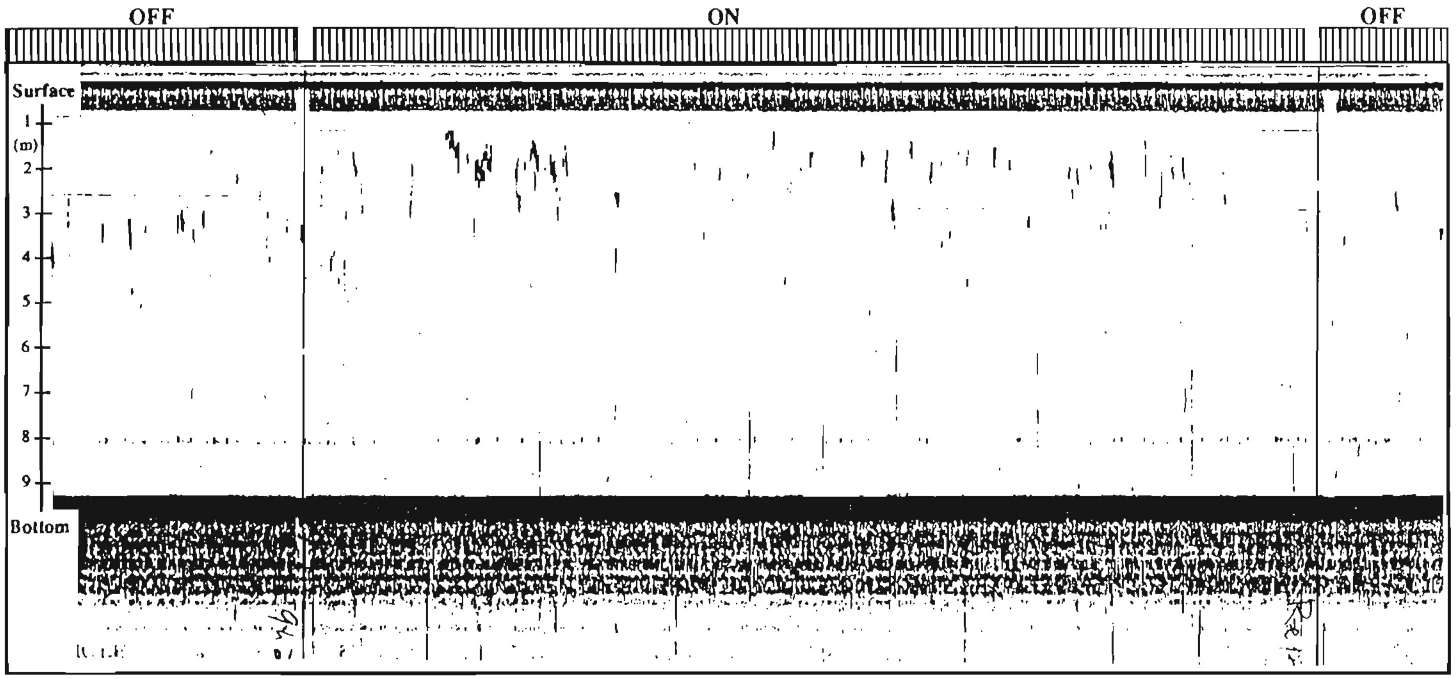

Figure 15. Acoustic deterrent effect on juvenile shad.

CONSIDERATION OF BEHAVIOUR OF ATLANTIC (*Salmo salar*) SALMON SMOLT IN FISHWAY DESIGN AT HYDROELECTRIC DAMS

by

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ABSTRACT

Long-term investigations of Atlantic salmon smolt migratory behaviours were conducted at various high latitude field stations. Experimental evidence show that variations in downstream migration intensity and selection of migratory routes are governed by smolt defensive behaviour. Abiotic and biotic factors contribute to increased smolt survival and change smolt response thresholds, thereby intensifying downstream movements. It is hypothesized that, if water in the forebay of a dam is characterized by preferable conditions, it may be possible to attract smolts to the head part of the passage facility thereby improving fish passage and survival.

INTRODUCTION

Naturalists, hunters and trappers are aware that various animals have specific migration routes. However, it is important to note that migrations do not merely follow paths through various localities but are complex movement patterns affected by environmental factors that vary seasonally as well as diurnally.

Fishways are successful when they simulate natural passes. Field investigations were therefore conducted to determine the behaviour of wild smolts in the context of fish passage through dams. An important objective of this study was to characterize smolt behaviour under natural conditions. Such investigations are important if one is to develop fishways that will enhance runs of Atlantic salmon smolts.

STUDY AREA AND METHODS

The investigation was carried out in the Arctic under 24 hour light conditions at four rivers emptying into the White Sea (Porya River 1975, 1980, 1982; Luvenga River 1978, 1979, 1981; Varzuga River 1990 and Soyana River 1968-1975 and 1979). Figures 1a and b illustrate a typical study site. An observation tower was constructed in mid stream, at each site. A long line was stretched across the river, upstream from the observation tower, and live or model pike (*Esox* spp.) were attached to the line. Ceramic tiles were evenly spaced along the centre line of the river, as a means of estimating distances. The river was mapped and surface, mid-water and near bottom water velocities were determined at various locations within each site. Parr, smolt and pike behaviours were observed over 24 hour periods using polarizing lenses. An imaginary line transecting the river at the observation tower was denoted as the control band. A more detailed description of the methodology is presented in Bakshtansky (1980) and Bakshtansky *et al.* (1987).

The rivers differ in size, number of smolts, limnology of the basin and hydrological characteristics such as water transparency. Parr are found upstream at the Porya site and near the estuary at the Varzuga site; whereas the Luvenga River flows through several lakes. Data were obtained from different rivers to gain an insight into the effect of varying interrelated abiotic (water chemistry, weather, stream discharge, and light intensity) and biotic (predators and schooling behaviour) factors.

Our research addresses the following questions:

1) Why do smolts choose to migrate in bright daylight and how do various abiotic conditions affect migratory intensity?

2) Why do migrating smolts avoid deep-water sites even when pike are absent?

3) How does smolt behaviour change as migrations progress?

4) How do predators affect migratory behaviour?

The first question was answered by fixing a selenium photocell near the river bottom at the entrance to a fingerling trap and recording fish movements and light intensity. Diffuse light created by overcast conditions was recorded as a thin, smooth line; whereas bright sunlight was recorded as a broad jagged band.

RESULTS AND DISCUSSION

Migration intensity was directly related to an increase in light intensity (Figure 2) (Bakshtansky and Nesterov 1974a, 1974b). However, multiple correlation analysis of downstream migration suggested that no one factor governed the movement of smolts on the Soyana River between 1968 and 1974 (Figure 3). Water level (1968, 1972 and 1974), atmospheric pressure (1969 and 1973), water temperature (1971), and the duration of sunlight (1970) influenced fish movements. The number of migrating smolts and migratory speeds depended upon several factors that varied between years. Water level, temperature and duration of sunlight governed the 1968 migration intensity. In 1970, the intensity depended upon the duration of sunlight and atmospheric pressure (Nesterov *et al.* 1985).

The 1965-1975 Soyana River data suggested that smolt migrations begin within 30 to 51 days after the average water temperature reaches 0.1°C (Nesterov 1981). Therefore, the date at which average temperature reaches 0.1°C may be used in predicting migratory onset. As illustrated by Figures 4a, b and c, the actual migrations began when the average water temperature reached 10.0°C.

Relationships between migration intensity and abiotic conditions were distinctly expressed among Porya River smolts. They usually migrated during bright conditions, whereas movements ceased during periods of low light intensity (Yakovenko 1974; Bakshtansky *et al.* 1976a).

Observations (July 16-17 and July 21-22, 1980) of seven early stage parr indicated that active feeding and movement patterns were related to light intensity. They were active between 7 a.m. and 10 p.m. (Figure 5). Parr sought shelter when light intensity decreased.

Three parr observed over a six day period became active between 8 a.m. and midnight when light increased from 4,500 to 45,400 lx. The parr were most active (66% of the active time) when illumination ranged between 16,000 and 80,500 lx. They returned to their shelter between midnight and 8 a.m. when light intensity dropped to between 1,200 and 14,100 lx (Figures 6a and b). When the weather was overcast, they made several short (< 15 minute) forays from their shelter. They spent a total of approximately 2.5 hours per day away from cover, even though food availability increased (a reduction in brightness stimulates drift of allochthonous and autochthonous organisms).

These observations were reflected in the migration patterns of single and schooling smolts. Single smolts migrated when brightness exceeded 0.8 lx. The correlation coefficient between migration intensity and light intensity was 0.94 ± 0.05. Schooling smolts usually migrated when light exceeded 20,000 lx, from 4 a.m. until 5 p.m.

Small (3-5 cm) and large (6-11 cm) parr were usually found in water velocities of 0.075 and 0.152 m/s, respectively (Bakshtansky *et al.* 1982; Bakshtansky and Nesterov 1983)(Table 1). As suggested by Table 1, the surface water velocity was, on average, more than 5.2 times greater than the water velocity at the holding position of small parr. The surface water velocity: water velocity at holding position ratio for large parr was 3.4:1.

Parr densities were directly proportionate to water velocities but, as water velocities increased, the size of guarded territories decreased. For example, an observer could approach to within 1.5 m of a parr when the water velocity was greater than 0.5 m/s. This was not possible at lower water velocities. When parr were in high velocity water currents, they often swam near pike (1-1.2 m). The increase in tolerance with increase in velocity supports evidence that such conditions represent a form of shelter for parr.

Smolts change physiologically as they migrate, therefore, their behaviours and the effects of environmental conditions change as migrations progress. The spawning grounds in the Porya River are located 3-15 km from the mouth. The schooling behaviour of migrating juveniles was studied from June 15 until July 6, 1980. Of 1032 observed smolts, 17% migrated through the control band as individuals, 21% migrated in groups of 2-4, 13% moved in groups of 5-7, and 49% moved in groups of 8-35 animals. The frequency of occurrence of groups were as follows: 56.3% consisted of individuals, 25% consisted of 2-4 smolts, 9.4% consisted of 5-7 smolts, and 9.3% consisted of 8-35 smolts.

The observations indicated that half of all groups (51%) migrated with a downstream orientation. Individuals within groups consisting of 2-4 and 5-7 smolts periodically reversed their orientation. However, animals swimming alone, or in groups of more than 8 smolts maintained downstream orientations (Figure 7).

The average migration speed was highest among groups of 8 or more smolts. The high relative speed of large groups may be attributed to maintaining a downstream orientation. The slowest speed was found among groups of 2-4 smolts and was due to orientation switching. Individuals and groups consisting of 2-4 smolts (~ 50%) migrated near the bottom. Many of the other fish migrated in mid-water, or near the surface where the velocity of flow was the greatest (Figures 7A-C).

Animals migrating near the bottom were particularly susceptible to attacks from parr (Table 2). Sometimes, parr pursued smolts for a distance of 12 m affecting their behaviour greatly (Figures 8 and 9).

The downstream migration of smolts is a critical period, therefore, all forms of camouflage are important to survival. Fish that travel near the surface may rely upon sun flashes in the Arctic, whereas turbidity may provide migratory shelter in temperate climates.

Individual smolts migrating near the bottom sometimes moved very slowly and tried to hide. Smolts that lost their shelter under a stone tried to find replacement hiding places. When these smolts moved too close to parr territories they were attacked and quickly zigzagged toward the surface where they fell prey to pike.

As the migration of schooling smolts proceeded, they became more defensive. The speed of schooling smolts increased and the relationship between migration intensity and environmental factors weakened. Obstacles such as a seine net set across the mouth of the Varzuga River caused some fish to swim 1.5 km or further back upstream.

Predators greatly influence smolt behaviour. Long-term observations show that predators interfere with the migration of pink (*Oncorynchus* sp.) and chum salmon (*Oncorynchus* sp.) (Bakshtansky 1963, 1970, 1980). Observations made at the Soyana River in 1973 indicate that sun flashes may provide cover for migrating smolts (Bakshtansky and Nesterov 1974a). A study of pike behaviours in a lake within the Soyana River basin suggests that the greatest hunting activity occurred between 8 p.m. and 5 a.m. when light intensity dropped below 15,000 lx. Hunting peaked between 10-11 p.m. when brightness was between 1,200 and 3,000 lx. Pike were not seen hunting during bright sunlight conditions (Bakshtansky *et al.* 1976a, 1976b). Normally, Soyana and Porya run intensities decreased as pike hunting activity increased (Figure 10). However, the Porya River held a much larger population of pike than the Soyana River and pike often ate 1/3 of the Porya River smolt population. During 1975 and 1980, pike hunting activities increased from 10 a.m. until 4 p.m. and decreased between 10 p.m. and 4 a.m. (Figure 11). Regression analysis of 155 continuous hours of observation of migratory intensity and daytime pike attacks produced a correlation coefficient of 0.671 ($P=0.95$).

Pike achieved the greatest hunting success when they preyed upon smolts that were displaced by parr (Figure 12). It is important to note that predators and prey interacted with each other according to complicated responses based on their life experiences. It was evident that pike could hunt more effectively in scattered light, however, smolts and parr usually avoided these conditions. Young salmon must realize that when light intensity and water speed decrease, the number of potential dangers increase, so they stop feeding and hide under stones (parr) or remain for long periods of time in places where the velocity is high (smolts) (Bakshtansky and Nesterov 1976).

Migrating smolts sought shallow, fast flowing water as refuge from danger. Smolts became easily frightened when in slow, deep water. Pike were often found in slow, deep water, therefore these areas will be referred to as "potential pike areas" (Figures 1a and b).

The behaviour patterns of individual and schooling smolts differed considerably when they came into contact with pike (Figure 1a). Sixty percent of the individual smolts rushed over the control line after zigzagging once or twice in front of the pike. Whereas 63% of the schooling animals crossed the long line after an average of 7.5 attempts. Therefore, migrations could be delayed by simulated danger. Delays were greater for schooling smolts than for individuals (Bakshtansky *et al.* 1980).

According to V.A. Pupyshev (Bakshtansky *et al.* 1977), a pike's vision becomes obscured by light from above. This could explain the observation that pike allowed underwater researchers to approach within 1.5-2.5 m on overcast days and 0.5 m on bright days. The silver bodies of smolts are probably hidden by ripples on bright days.

Lakes may cause smolts to slow or cease their migration, therefore impoundments greatly influence the survival of migrating smolt. For example, some smolts within the Luvenga must swim through a 0.75 and a 2.2 km^2 lake that are respectively 23 and 14 km from the river's mouth. Smolts remained in the lakes for relatively long periods of time and often did not reach the sea until almost a month after smolts that start migrating from below the lakes. The delay could be due to a loss of orientation, or due to favourable feeding conditions within the lake. It has been hypothesized that migrations began as the result of searching for abundant food resources. Experiments have shown that the swimming activity of Atlantic salmon juveniles is directly dependent upon the availability of food. They can be compelled to remain in an area, move downstream or move upstream by manipulating food delivery (Safonov and Bakshtansky 1990).

CONCLUSIONS

The data provide evidence that changes in speed, intensity of downstream migrations, and selection of migratory routes are governed by smolt defensive behaviour and variations in threshold responses. Smolt behaviours and migration intensities are greatly influenced by various factors (light intensity, water temperature, the presence of predators, the antagonistic behaviour of parr, sizes of downstream migrating schools of smolts etc.). Man must take all of these factors into account if his fishways are to enhance the downstream movement of Atlantic salmon smolts.

ACKNOWLEDGEMENT

We are greatful to everyone who recorded the observations. We especially wish to acknowledge the contribution of M.N. Neklyudov, Head of the Observation Station at the Porya River, Polar Research Institute of Marine Fisheries and Oceanography (PINRO). A.A. Loenko and V. Isaev (laboratory workers at PINRO) aided in the study of migrations within the Luvenga River. M.A. Draganov (Fishery Biologist at Murmanrybvod) made observations at the mouth of the Varzuga River. V.A. Pupyshev (senior research worker at VNIRO) conducted a series of experiments at our request. S. Chenchenin, A. Morozov (workers of VNIRO and PINRO), as well as E. Kopylova, S. Kulichenko, O. Zakharov, N. Doktor and A. Bukina (students and trainees) took part in the experiments.

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Table 1. A comparison between surface water velocities above Atlantic smolts and water velocities at the depth at which they were found.

Size (cm)	No.	Mean Depth (cm)	Flow Velocity (m/s) at start points min	max	mean	in surface layer	Surface Start Point Ratio *
3.0	2	34.0	0.04	0.13	0.085	0.595	7.0
3.5	7	32.0	0.04	0.15	0.074	0.297	4.0
4.0	6	39.7	0.03	0.17	0.070	0.367	5.2
5.0	5	41.4	0.04	0.13	0.080	0.422	5.3
6.0	4	34.0	0.12	0.21	0.134	0.610	4.6
7.0	11	33.8	0.05	0.29	0.121	0.360	3.0
8.0	6	29.7	0.10	0.38	0.195	0.522	2.7
9.0	3	35.3	0.06	0.26	0.193	0.527	2.7
10.0	6	36.5	0.08	0.29	0.156	0.318	2.0
11.0	4	32.0	0.13	0.18	0.155	0.435	2.8

* Ratio of surface:depth velocities

Table 2. A summary of parr attacks upon smolts.

Number of Smolts per Group	Frequency of Occurence	Number of Attacks	% of Smolts Attacked	% of Smolts Migrating Near Bottom
1	218	27	12.4	53.8
2 - 4	97	9	9.3	50.0
5 - 7	28	1	3.6	30.7
8 - 35	44	1	2.3	5.6

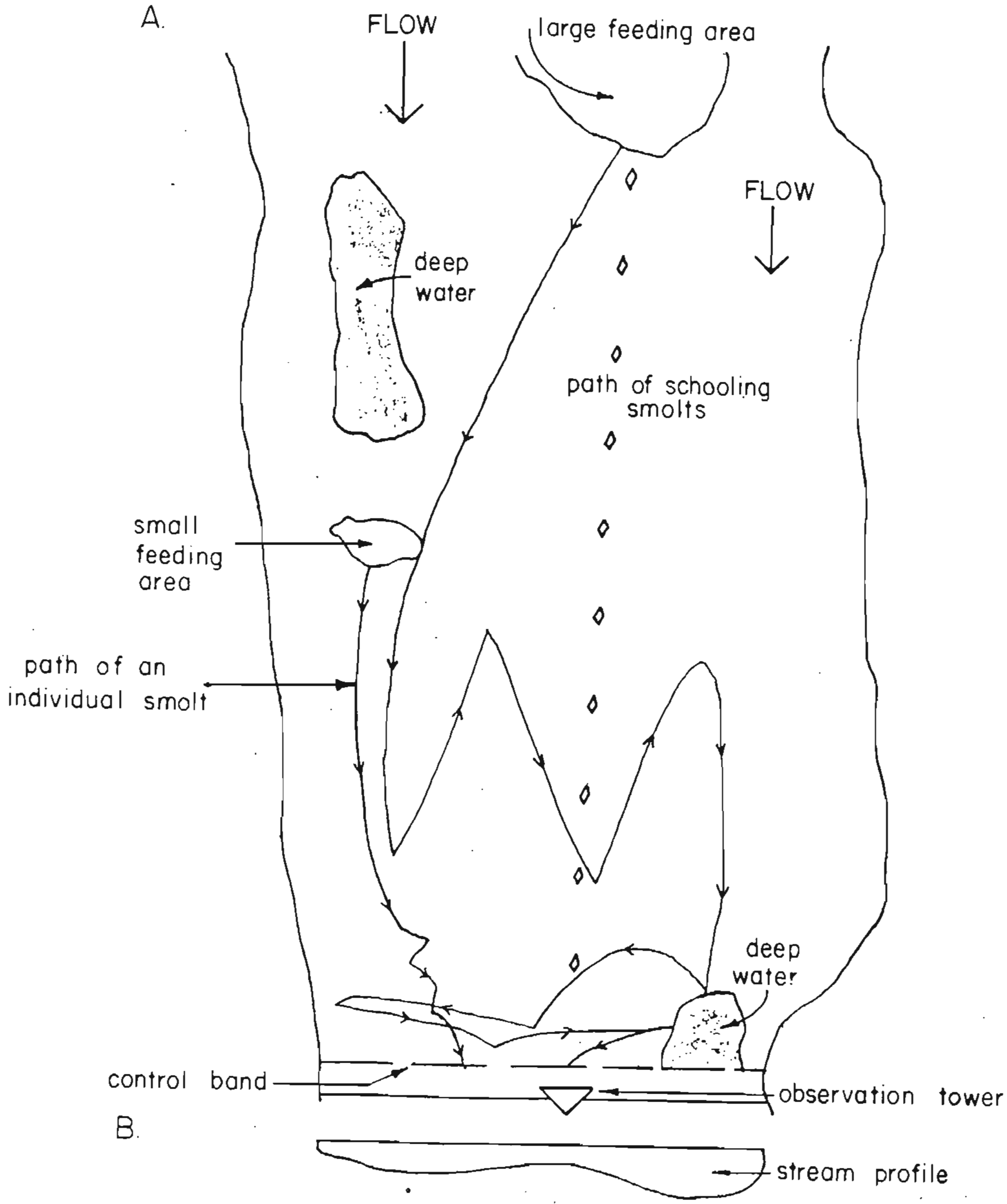
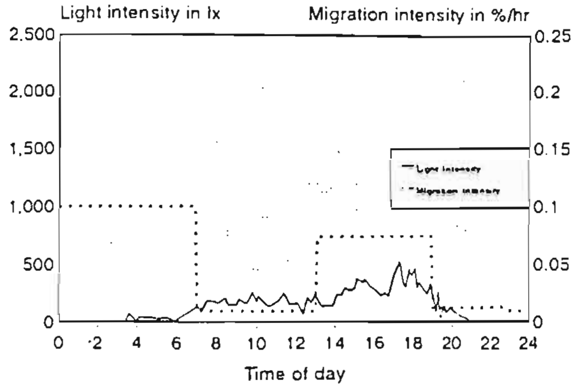
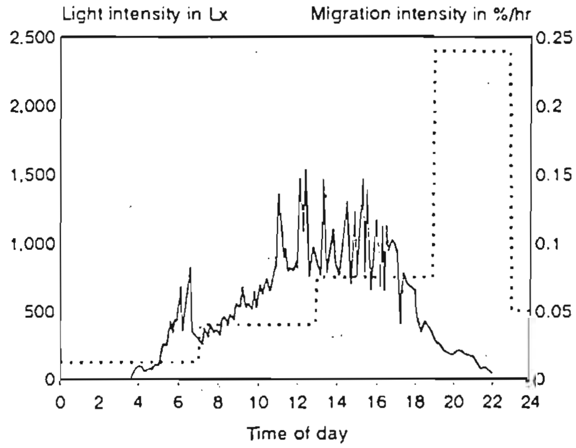


Figure 1A. Smolt movements within the Porya River site.

Figure 1B. River profile at control band.



July 17



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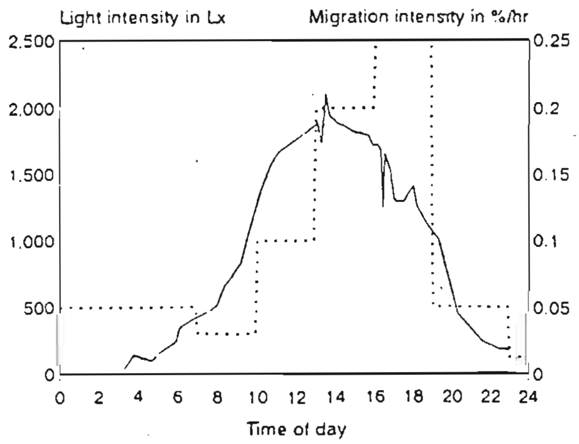
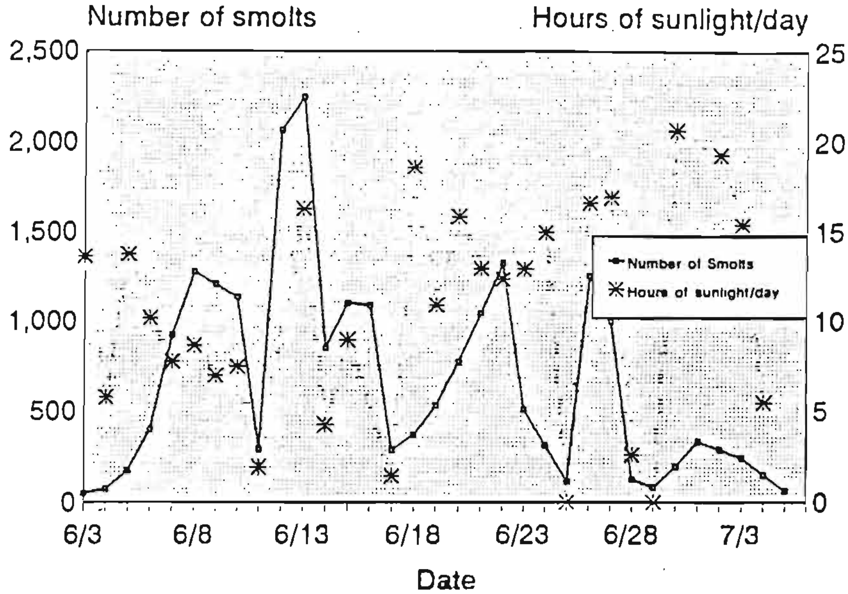


July 24

Figure 2. The effects of illumination upon the intensity of the Soyana River Atlantic salmon smolt migration (July 17, 18 and 24, 1974).



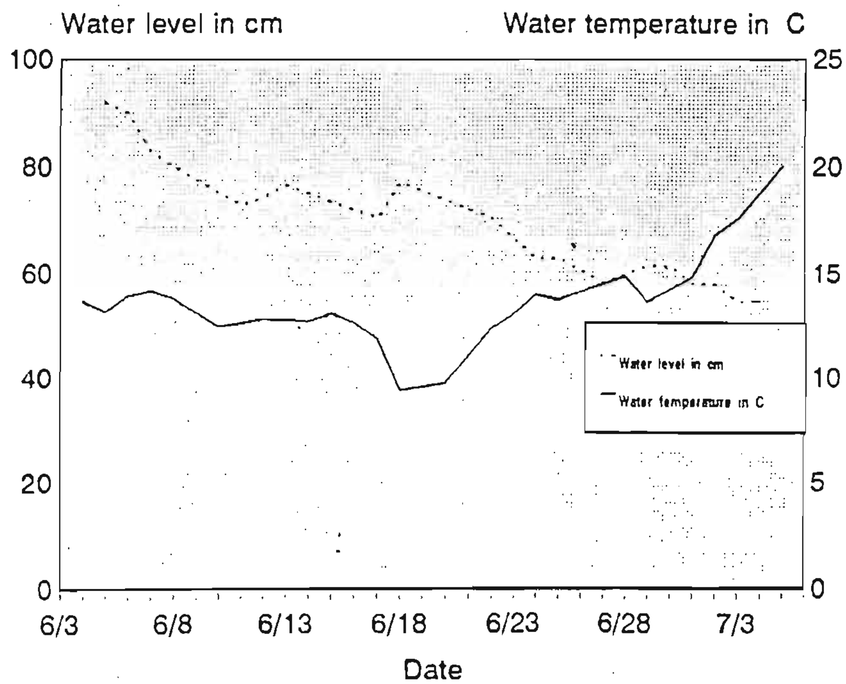
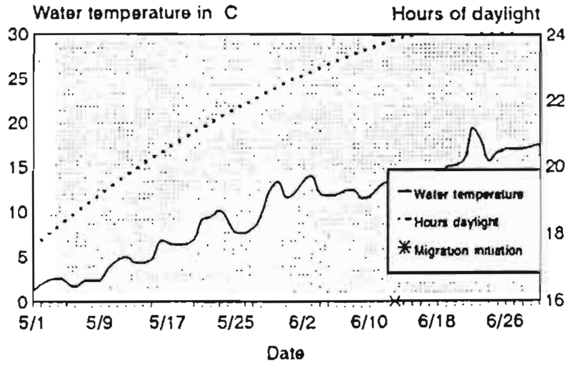
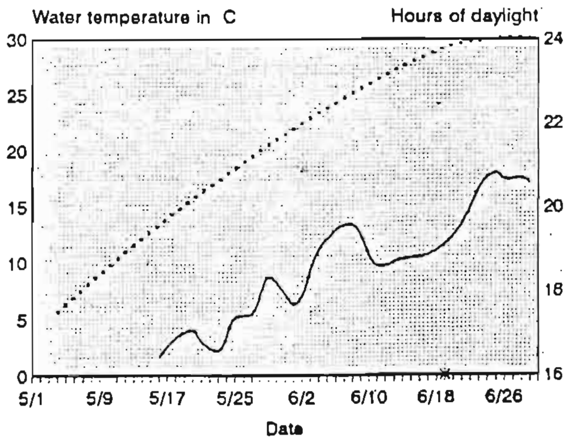


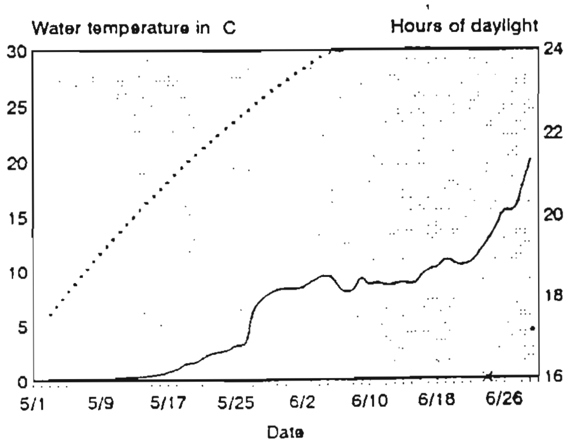
Figure 3. Intensity of the 1973 Soyana River Atlantic salmon smolt migration in relation to hours of sunlight, water level and water temperature.



1967

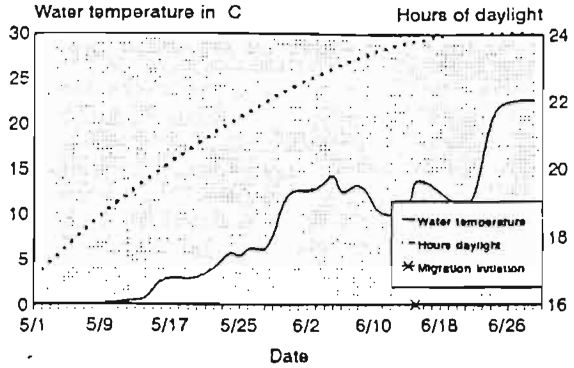


1968

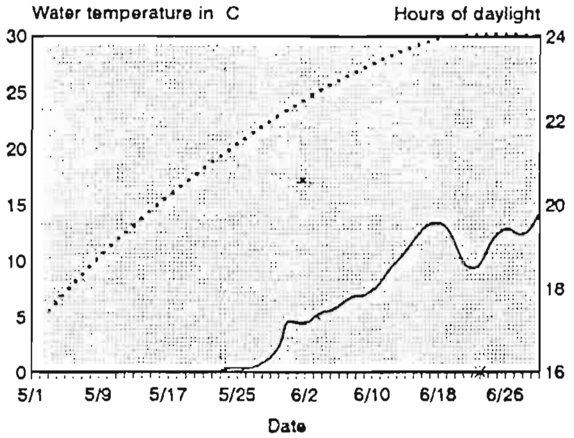


1969

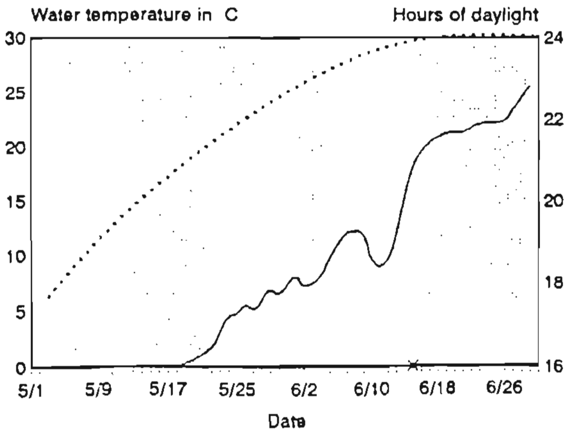
Figure 4A. Soyana River Atlantic salmon smolt migration initiations in relation to water temperatures and hours of daylight (1967-69).



1970

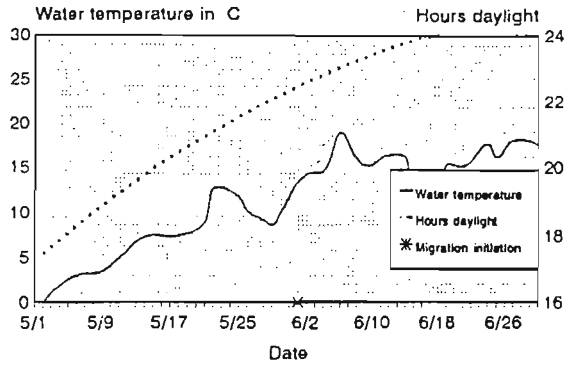


1971

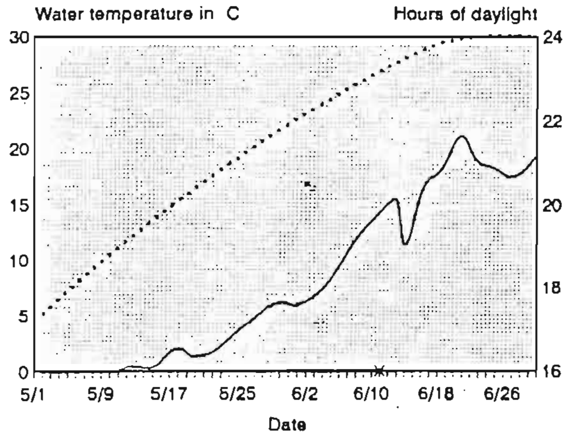


1972

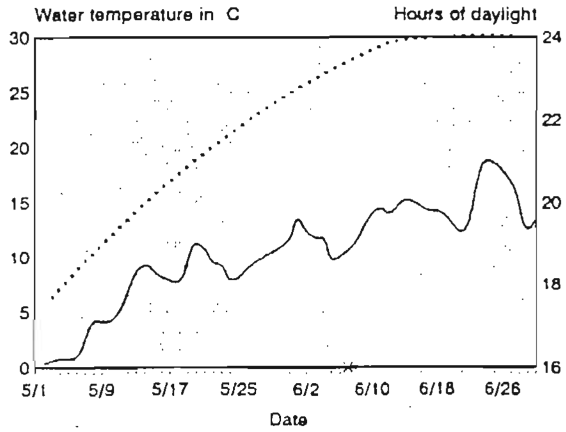
Figure 4B. Soyana River Atlantic salmon smolt migration initiations in relation to water temperatures and hours of daylight (1970-72).



1973

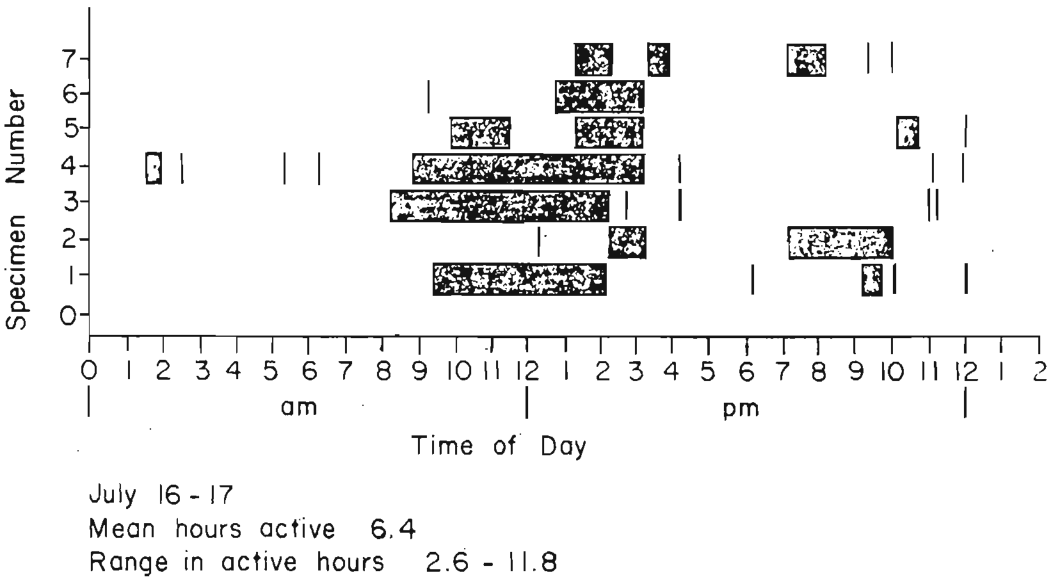


1974



1975

Figure 4C. Soyana River Atlantic salmon smolt migration initiations in relation to water temperatures and hours of daylight (1973-75).



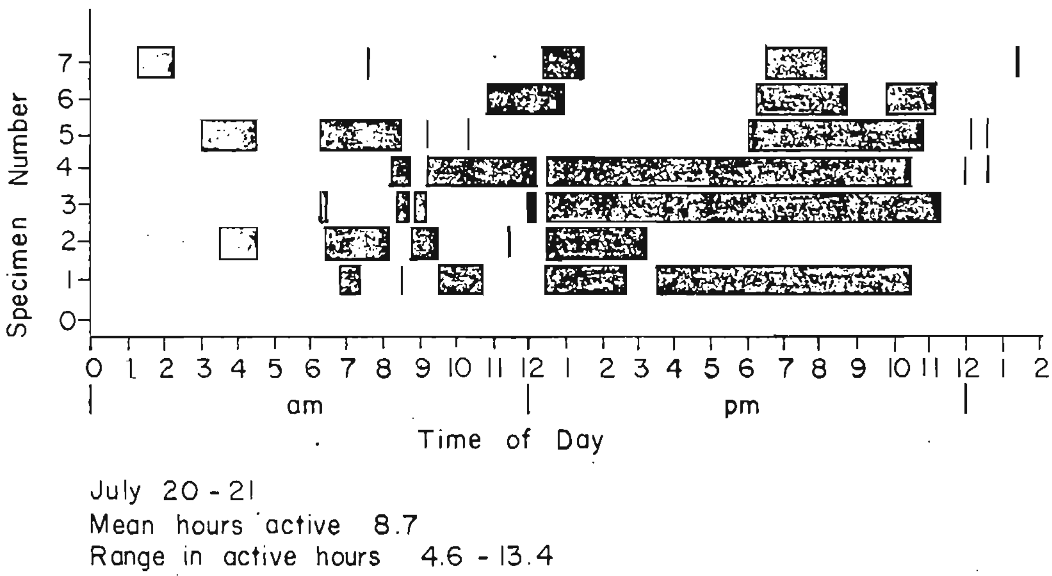


Figure 5. Diurnal activity rhythm patterns among 7 Porya River parr (1980).

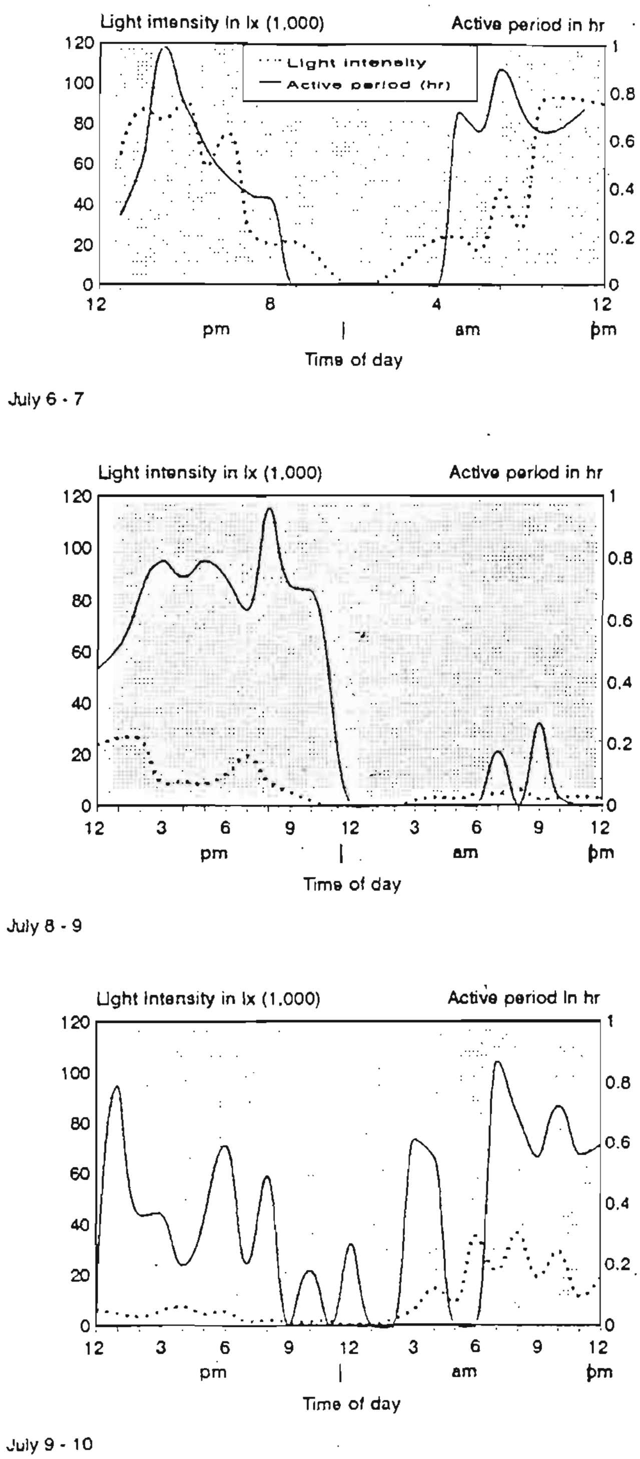
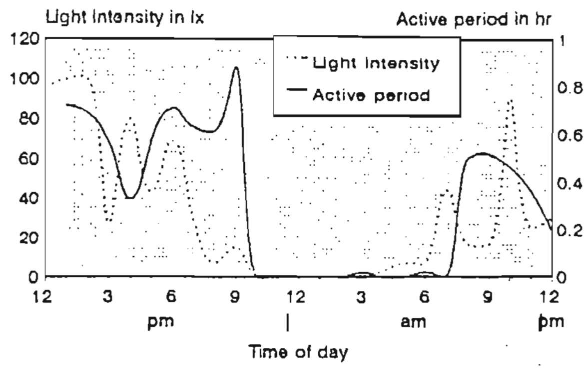
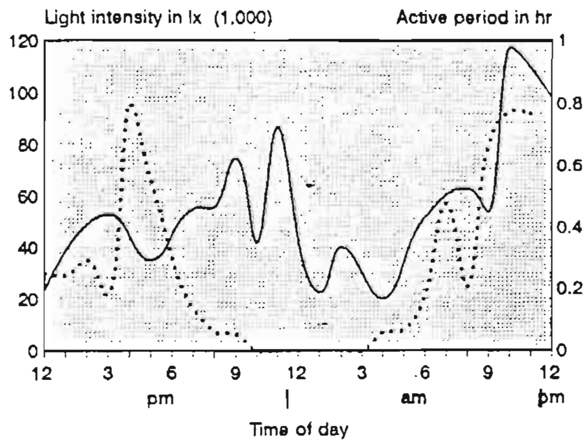


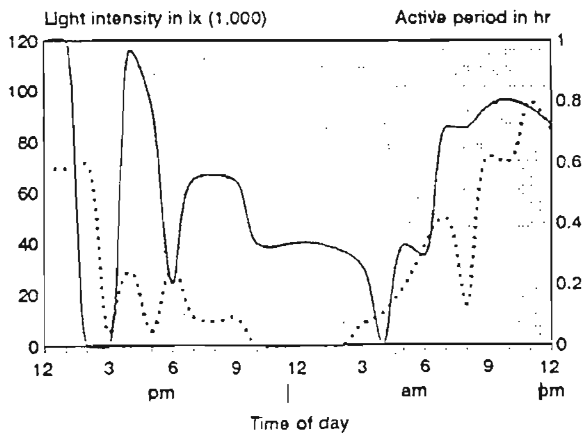
Figure 6A. Effects of illumination upon 1982 Porya River parr activity levels.



July 13 - 14



July 14 - 15



July 18 - 19

Figure 6B. Effects of illumination upon 1982 Porya River parr activity levels.

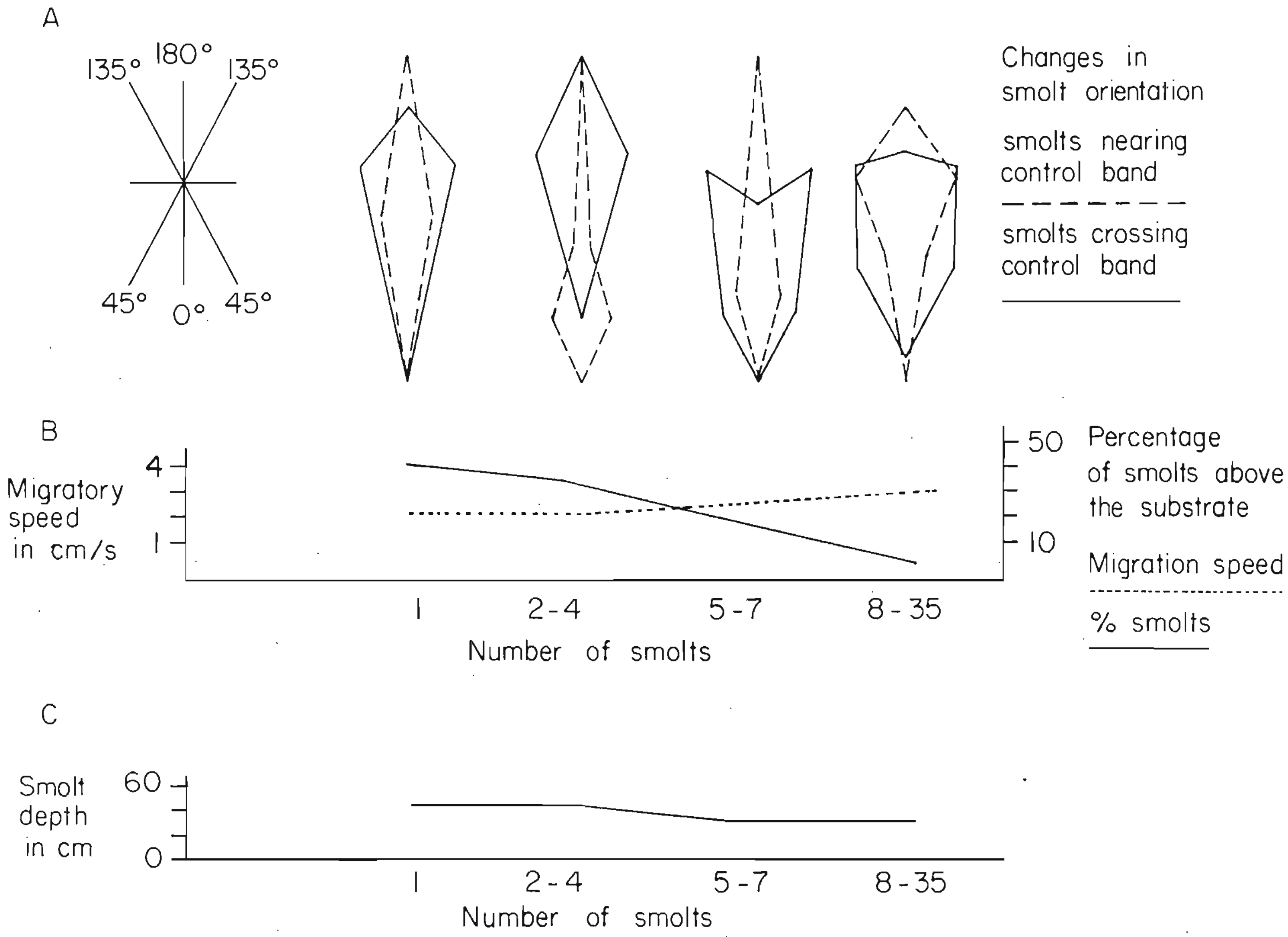


Figure 7A. Changes in orientation of various sized schools of migrating smolts as they approached (- -) and passed over (__) the Porya River control band (1980).

Figure 7B. School size as it affected relative number of smolts swimming near the bottom (- -) and their migratory speed (__) as they passed over the Porya River control band (1980).

Figure 7C. The average depth of various sized schools of smolts passing through the Porya River control band (1980).

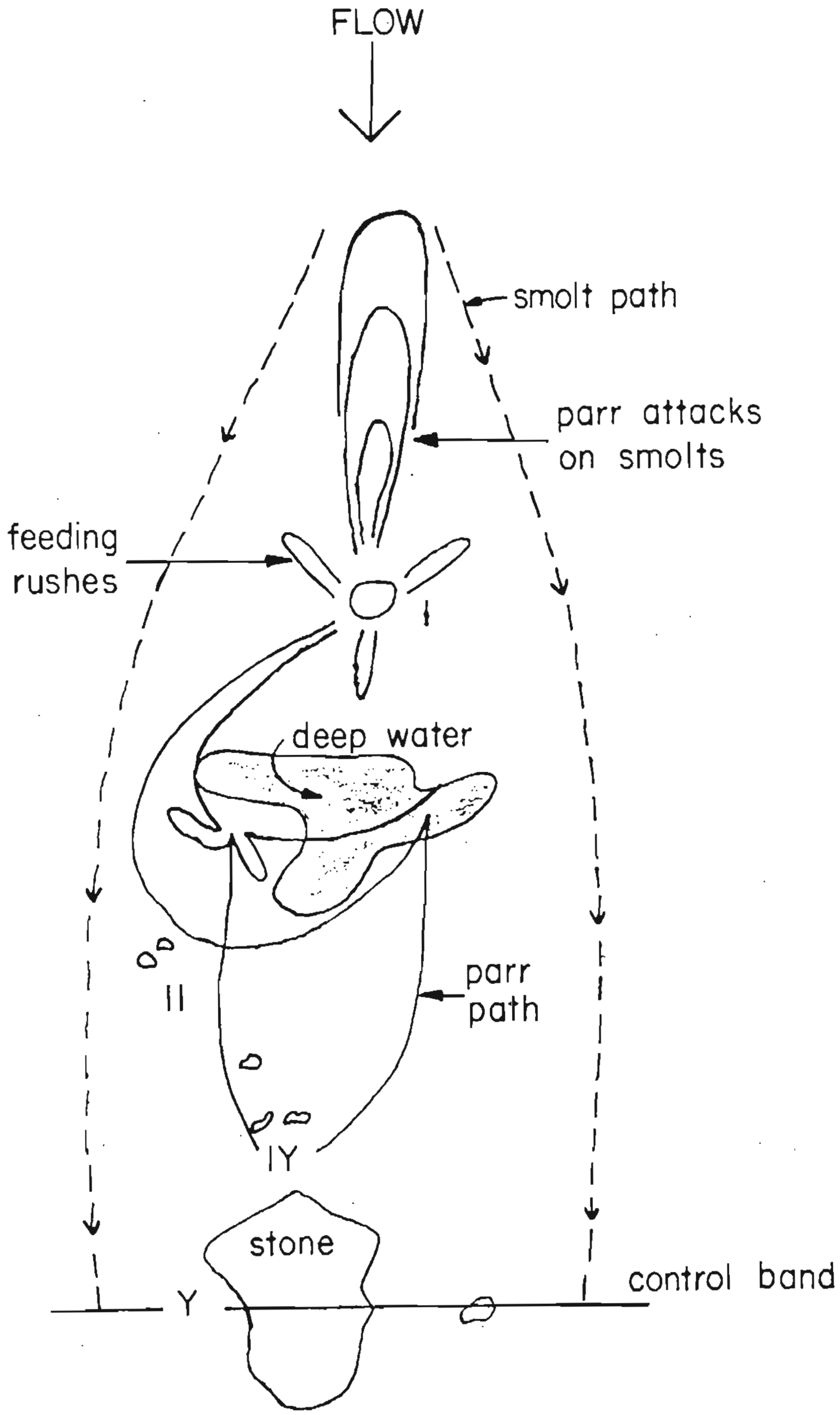
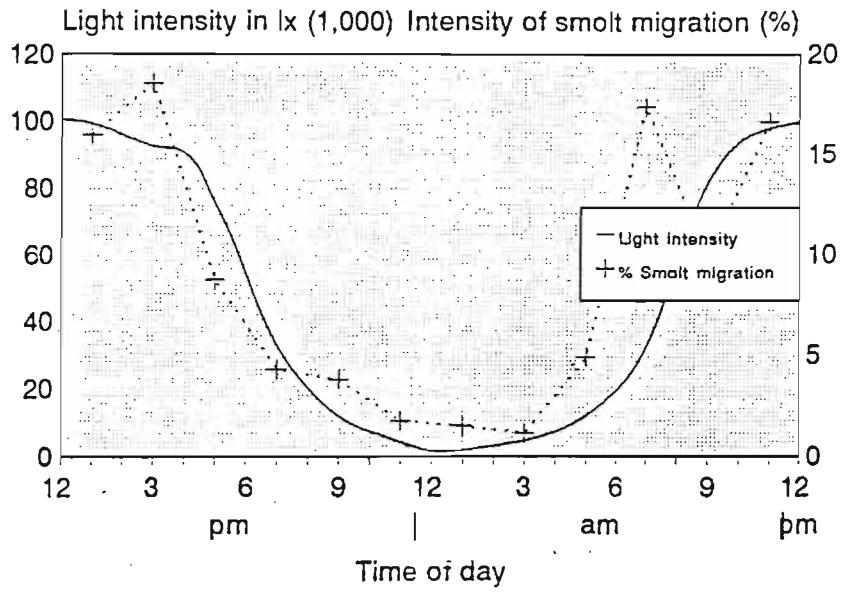


Figure 8. Parr movements within a territory.
I - start point
II - IY resting places
Y - refuge



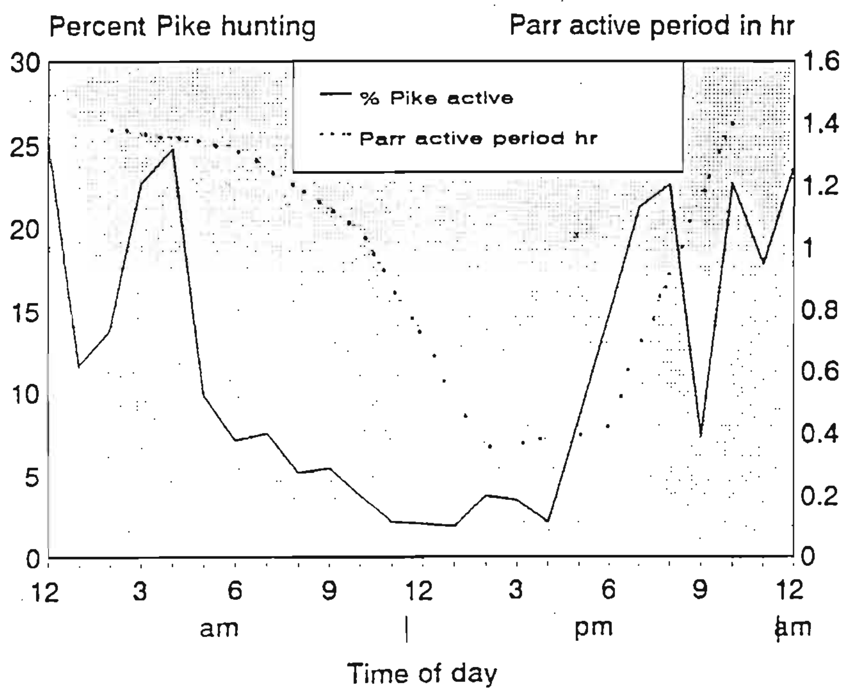


Figure 9. Porya River pike, Atlantic salmon parr and smolt activities in relation to light intensity.

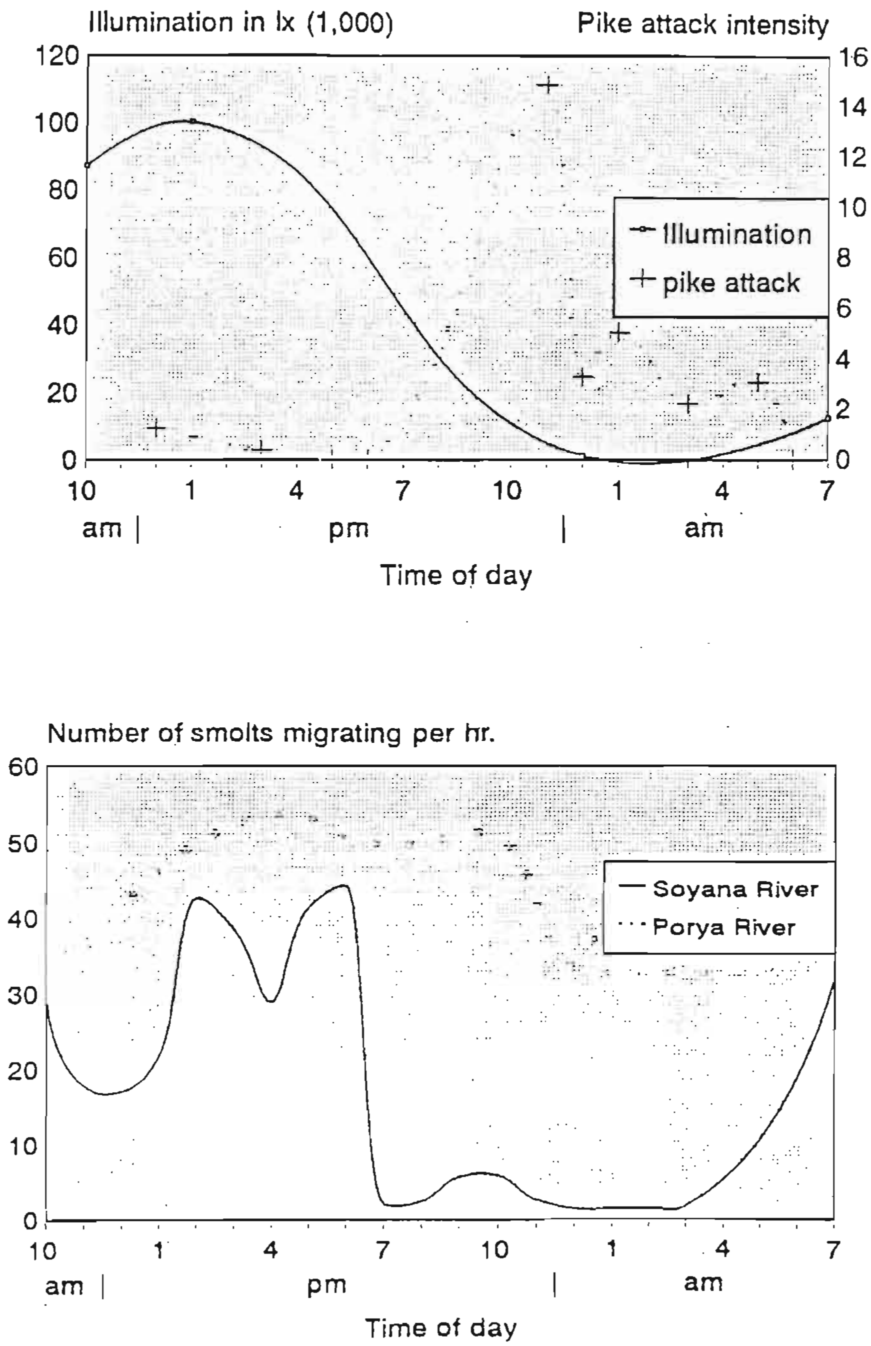
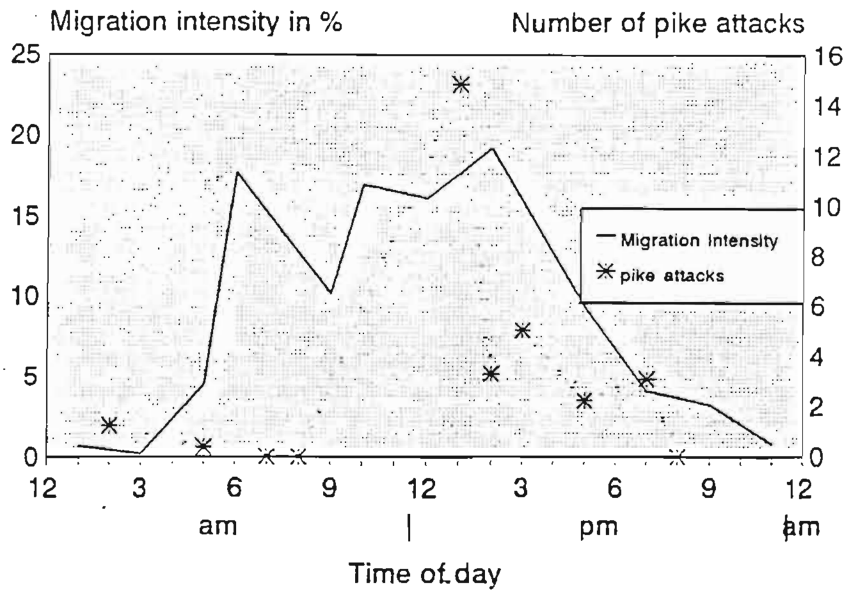


Figure 10. Pike attack intensity in relation to light intensity and Atlantic salmon smolt migration intensity (Porya River 1975 and 1980).



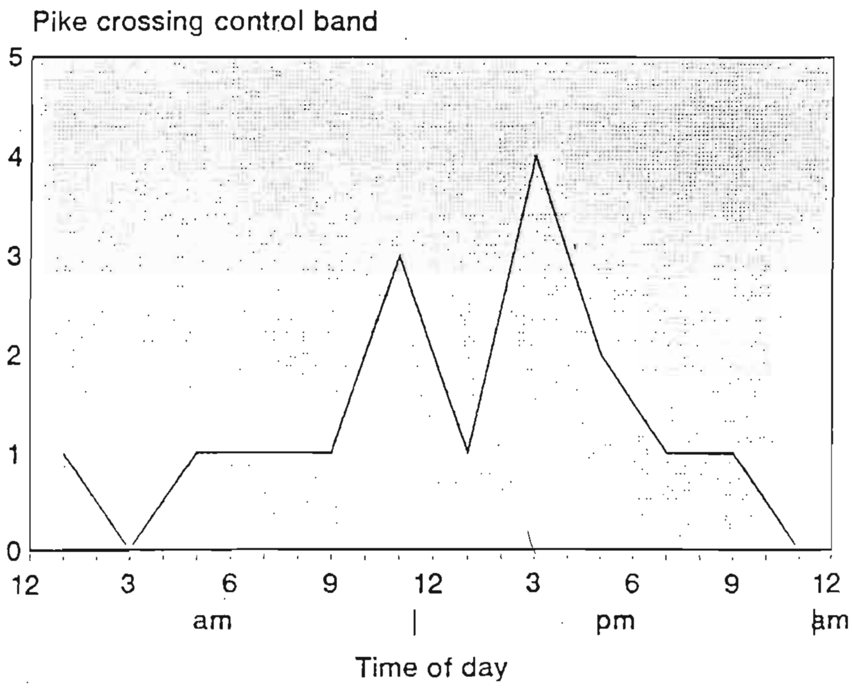


Figure 11. Diurnal patterns of pike and Atlantic salmon smolt activities at the Porya River site.

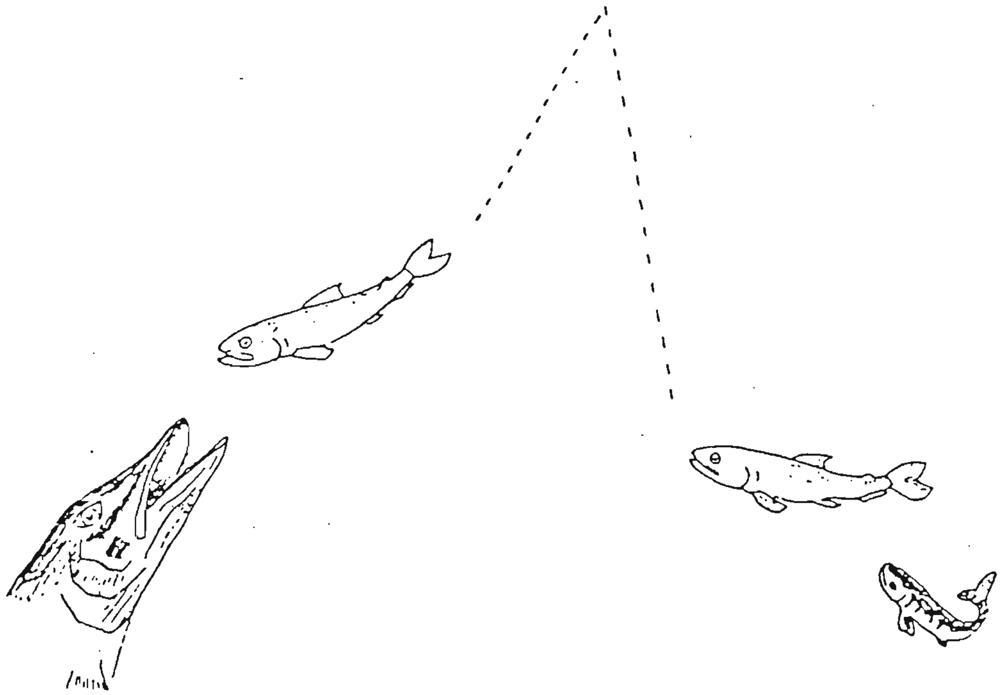


Figure 12. Pike attacking an Atlantic salmon smolt that had been chased by a parr.

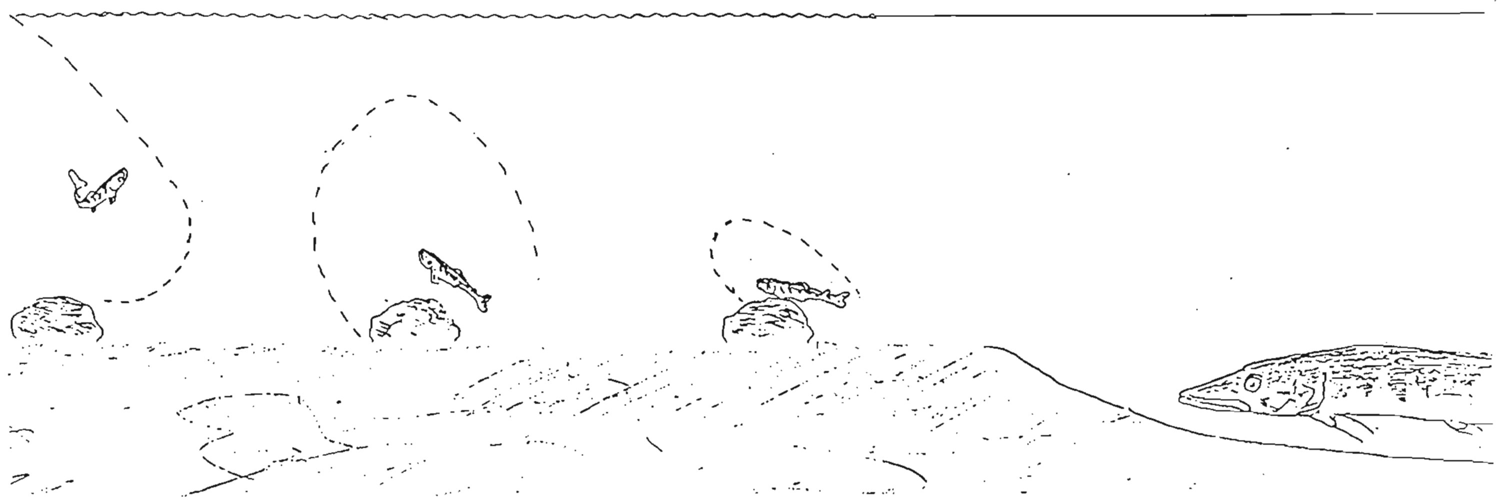


Figure 13. Distances that parr will travel from shelter is directly proportional to distance from pike.

WORKSHOP CONCLUSIONS

This publication represents the proceedings of a major workshop that discussed issues related to upstream and downstream fish passage and to ascertain the effectiveness of: (1) various data collection methodologies, and (2) forms of technology allowing passage. Due to the economic importance of Atlantic salmon within the Newfoundland Region, the workshop emphasized passage of this species. There are a number of complex biotic and abiotic factors that must be taken into account when developing mitigation to facilitate salmon passage at hydroelectric facilities. Abiotic factors include water discharge rates, water velocities, penstock design and turbine type while biotic factors include schooling, rheotactic and stimulus-response behaviours, swimming capabilities and the presence of predators.

Forebay and power canal structures must be designed such that fish are able to easily find a safe downstream path. Designs must take into account the fact that migratory fish will be attracted to high velocity water currents within the forebay. Fish that are not able to resist powerful flows, or are not directed towards a bypass system, may be entrained at the penstock intake and as a result will pass through the turbine.

Entrained fish passing through turbines encounter sudden changes in water pressure, shear effects, effects of cavitation, and physical damage caused by contact with a turbine structure. Studies indicate that choice of turbine, percent wicket gate opening, the efficiency of plant operation etc., as well as the species, size, and health of fish influence the extent of turbine related injuries and mortalities.

Behaviourial and physical barriers as well as collection and diversion systems have been used in an attempt to prevent passage of fish through turbines. None of these technologies have been proven to be 100% effective and the variable success rate may be attributed to the unique set of circumstances presented by each hydroelectric development. It is crucial for individuals inputting into the design of a particular system that they are aware of past applications as well as their successes and failures.

There are a number of factors which can influence mortality at any given powerplant. Factors such as species, fish size and condition, temperature and oxygen concentrations, concentrations of dissolved gases etc. can greatly influence the validity of a study. A number of studies have been conducted in an attempt to determine experiment related stress, however, results become unreliable once control mortalities exceed 10%. Controls do not account for the cumulative effects of passage and experiment related stresses.

Even if fish successfully bypass hydroelectric developments, the bypass system must take into account the possibility that predators may concentrate near the outflow. Therefore, the behaviours of predators as well as smolts must be taken into account.

The question of the expectation imposed by some regulatory agencies of 100% safe passage contributes to the lack of a widespread acceptance of any particular method of downstream fish passage. In spite of years of research and development, a system to meet this criteria that would be practical to construct and operate while remaining cost effective has not be developed. Therefore, while a great deal of innovative research and development has been conducted, there remains much more work to be done before practical solutions to the problems of fish passage at hydroelectric developments may be realized. The problems associated with the co-existence of anadromous fishes and hydroelectric facilities are enormous. The solution must take into account the biological imperatives associated with anadromous fish conservation and the engineering and economic imperatives associated with hydroelectric energy production.

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The workshop was a success because of the work of all those involved. We would like to thank the authors and participants for their contributions. Dr. M.B. Davis, Ms. K.A. Houston and Mr. L.J. Cole helped in organizing the workshop. We are also indebted to Ms. Houston for reviewing these proceedings.

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