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IMPACTS OF TURBINE PASSAGE ON DOWNSTREAM
MIGRATING EELS

by

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Report to: ELECTRICORP PRODUCTION

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IMPACTS OF TURBINE PASSAGE ON DOWNSTREAM MIGRATING EELS

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SUMMARY

Hydro-electric power generation places barriers across the pathways of migratory fish. For downstream migrants, often the only option is passage through the turbines. The primary question is whether these fishes survive.

There have never been any studies made of the survival of fish passed through turbines in New Zealand, although overseas studies have shown that mortality can be high. Increasingly, with the water permit process and claims for compensation and mitigation, Electricorp will have to consider the impacts of turbine passage on fish. It is obvious that a common question will be: "do fish suffer significant mortalities, particularly important species such as eels".

As a first step in providing the information necessary for good decisions, a review of the existing literature on turbine passage has been made. There is a considerable published information on the impacts of turbine passage on fish. Most of the effort has been concentrated on downstream migrating salmon smolts, although some studies have been made on eels,

largely in Europe.

Measuring mortality of fish after turbine passage is a difficult task. The fish are relatively small and dispersed within huge volumes of high velocity water. A range of attempts has been made to tackle the problem. Mortality rates appear to vary with turbine type, head, and the species of fish involved; survival is generally worst for longer fish.

Equations developed in Europe to predict eel mortality were applied to Karapiro and Matahina turbine parameters. The results indicate that eel mortality could be high, ranging from 45% to 100%.

A superficial, costly solution would be to screen the turbine intakes, but this approach ignores the basic biology of eels. Eels are committed to migrating downstream to breed. Therefore, unless they can escape from the reservoir in some other way, such as with water spillage, preventing eels from entering turbine intakes is only a half solution. The migrants will fail to breed. They will remain trapped within the reservoir, sustaining damage in their attempts to escape, and eventually dying.

Two alternatives are suggested: (i) to stop generation and to spill water over the nine or so nights in late summer when almost all the migration takes place; (ii) to trap the downstream migrants (tunaheke, silver eels, puhi) above the

turbines and release them downstream. Option (ii) has the least cost. There would be no generation losses, and the cost of trapping and release could be funded by sales of a portion of the catch. Migrant eels have a high commercial value, as well as sustaining an important Maori fishery. Electricorp could delegate responsibility for the operation to fishers commercial or Tangata Whenua).

Recommendations

1. Review spillway opening frequencies and match to dates for eel migrations.
2. Examine cost-effectiveness of deliberate shutdowns and water spillage during eel migrations.
3. Determine true mortality rates for eels migrating through Karapiro.
4. Examine cost-effectiveness of eel trapping.
5. Design an eel trapping system suitable for use within a hydro-electric reservoir, using a combination of light and/or louvre arrays to divert eels.

1. INTRODUCTION:

With great precision, Electricorp controls the water flowing from a significant portion of the catchments of New Zealand. With this control comes the assumption of at least some

responsibility for the aquatic resource. As a bonus, hydro-electric development has created large, productive, stillwater habitats. Appropriate management techniques are needed to maintain, restore, and possibly even improve those fisheries values affected by hydro-electric development. The purpose of this review is to identify major problems facing native fish above hydro-electric facilities and to suggest practical solutions.

The native freshwater fish of New Zealand have colonised from the sea. Most of them have retained marine links and migrate to and from the sea to complete their life cycles. Native fish have a number of values; including being very important to the Maori people. Eels in particular were a major source of lipid and protein to the pre-European Maori. The mana of tribes still depends upon the bounty that can be proffered on the marae. Eel and whitebait fisheries are commercially and recreationally important. Furthermore, native fish are links in the food chains which lead to trout and waterfowl. Native fishes also have their own intrinsic values as part of the unique fauna of New Zealand.

There is no reason why the production of native fishes could not be enhanced following hydro-electric development.

Electricorp-funded research into native fish passes has resulted in economical designs which will allow many species to continue their migration upstream past hydro-dams. In some areas, native fish can now gain access to habitat lost since

dam construction and can exploit new habitat created by impoundments. But consideration needs to be given to the passage of downstream migrants. Power generation demands that every drop of water available be put through the turbines. Included with the water are those fishes travelling downstream to complete their life cycles.

Fortunately, most native freshwater fish of New Zealand have fundamentally different life history patterns to the salmon and trout of the northern hemisphere. Instead of migrating downstream as smolt, greater than ten cm in length, native fish which are likely to occur in the habitats above hydro-dams migrate downstream as larvae, a few mm long. Limited published work (Cada 1990) available suggests that fish larvae tolerate passage through turbines relatively well.

However, there are three species of native fish which migrate downstream at a reasonable size: lampreys, which migrate downstream at around 10 cm in length, and the real giants, longfinned and shortfinned eels. The two eel species migrate downstream as mature, pre-spawning adults. By world standards, our freshwater eels are big, particularly the longfinned eel. Migrant female longfinned eels range from 80 cm to over one and a half metres in length. Males are from 50 - 70 cm long. Migrant female shortfinned eels range from 50 - 100 cm and males from 35 - 55 cm (Todd 1980). The size of New Zealand freshwater eels probably makes them particularly vulnerable to immediate or delayed mortality if they go through a turbine.

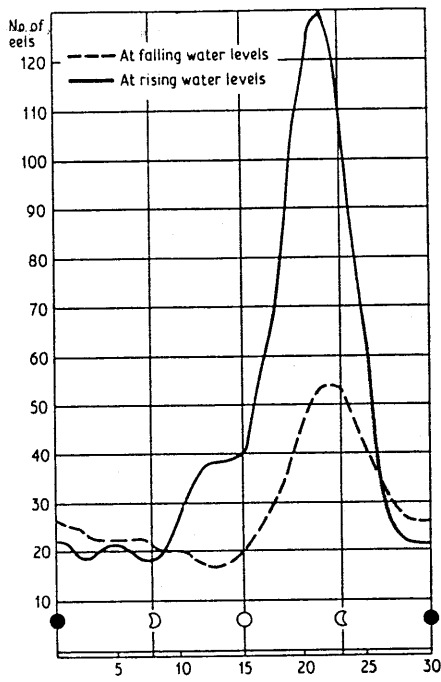
Eels must migrate downstream to the sea to breed. They swim to an unknown destination (perhaps in the deep ocean trenches near Tonga), spawn and then die. Juvenile eels (elvers) make the return journey back to New Zealand. Over spring and summer, elvers migrate up our rivers seeking out places to settle. It is then a long time before the fully grown eels make their return migration. Eels are slow growing, long lived fishes. Migrant female longfins examined by Todd (1980) were estimated to be from 25-60 years old. The smaller males were younger, from 12-35 years. Migrant female shortfins were from 10-35 years whereas male shortfins were 6-24 years old. These are all very respectable ages for a fish. Migrant eels may be older than the dams they encounter on their trip downstream.

Migrant eels are committed to migrating downstream. They stop feeding, mobilise their fat reserves, and undergo a complex metamorphosis. The increase in eye size (accompanied by a shift in retinal pigments appropriate for deep sea vision) and pigmentation, is so striking that these fishes are termed silverbelly eels (tunaheke to the Maori). Eels prevented from migrating out of intermittently open lakes, such as Ellesmere, will not feed again, but attempt to migrate the following year. Permanent screening of the outlet to a grass carp trial eventually resulted in the death of migrant eels above the screen (C.P. Mitchell pers. obs.).

Therefore, Electricorp faces the following scenario. Eels are a culturally and commercially valuable fish, which thrive in

the habitats created by hydro-electric power generation structures. There is growing pressure to restore the upstream migrations of elvers past dams, to the habitats formerly occupied by eels. The technology for elver passes is now available. But provision for the obligatory downstream migration is also necessary. Because they are both large and lengthy, eels are very vulnerable to damage during turbine passage. Our observations and reports from station operators are that dead and mutilated eels are common below dams during the migration period.

On the positive side, the main migration period is known and defined (Fig 1). Eels migrate at night, with 94.99% migrating shortfins being caught in February and March (Todd 1980). Migrations usually occur between days 17-25 of the lunar month (Tesch 1977). Longfinned eels migrate at the same time. The major peak in the number of eels migrating occurs when floods happen to coincide with the new moon (Burnet 1969, Palmer *et al.* 1987). The greatest catches are reported on rising floods, with catches falling off on subsequent nights (Lowe 1952). The migration period is also dependant on catchment area. Small catchments have a more sharply defined migration peak, whereas in larger catchments migration drawn out over more nights. This simply reflects the time that eels take to move down through the system.



A comparison of daily stow net catches in the Upper Rhine at rising and falling water levels, arranged according to the lunar month model

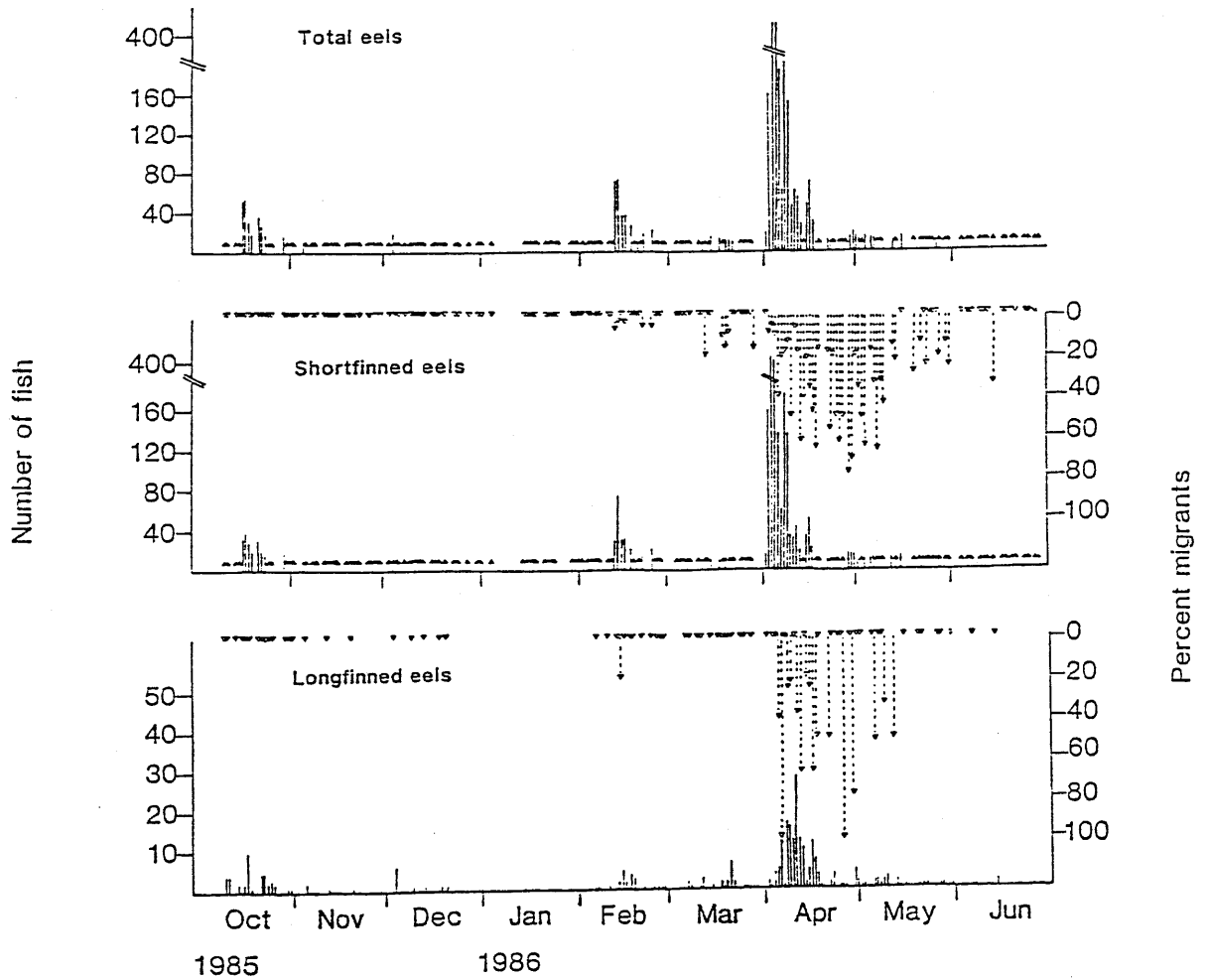


Figure 1. Eel migrations are predictable. Data from Europe (top) and Huntly, New Zealand (bottom).

2. THE IMPACT OF TURBINE PASSAGE ON EELS

2.1. Turbine designs

Turbine design has a major influence upon mortality rates for downstream migrants. Although it may be covering familiar ground for people with engineering expertise, a preliminary description of turbine design is given below.

There are basically two types of turbines: impulse turbines, such as PELTON, where the energy available is in the form of velocity, and reaction turbines, such as FRANCIS and KAPLAN, where both velocity and pressure are used.

Turbines have three basic elements:

- (i) regulating devices, which allow waterflow at the desired rate;
- (ii) the turbine itself, consisting of cups, runners, or blades;
- (iii) a diffuser (not used on PELTON), which allows the turbine to extract energy from the outflowing water.

PELTON turbines consist of cups arranged around a 'wheel'. A 'needle' allows the water flow to be regulated. These turbines are usually used on high head, low flow installations.

Water entering FRANCIS turbines is under pressure when entering the runner. Power output is varied by adjustable guide vanes or 'wicket gates' (Fig.3). FRANCIS turbines are the most common type installed at Electricorp facilities.

The KAPLAN turbine is basically of the propeller type (Fig.4). It is used where there are small heads and comparatively large water flows. The turbine usually has both adjustable guide vanes and blades.

All three types of turbine have been installed in New Zealand (Table 1).

Table 1. Type and rating of turbines from some New Zealand hydro power stations likely to influence eel migrations.

STATION	UNIT No.	MW	HP	NET HEAD	TYPE	No. OF BLADES
NORTH ISLAND						
Arapuni	1-4	18.7	25,000	52.4	FRANCIS	16
	5-8	22.4	30,000	50.9	FRANCIS	16
Karapiro	1-3	31.5	42,000	30.5	KAPLAN	5
Mangahao	1-2	2.4	3,225	251.5	PELTON	11
	3-5	4.8	6,450	251.5	PELTON	11
Matahina	1-2	37.3	50,000	60.4	FRANCIS	15
Kaitawa	6-7	15.7	21,100	129.3	FRANCIS	13
Tuai	1-2	16.7	22,400	192.3	Hor. Fran.	15
	3	20.9	28,000	192.3	Hor. Fran.	8+8
Piripaua	4-5	20.9	28,000	109.7	FRANCIS	11
SOUTH ISLAND						
Roxburgh	1-8	40	-	76	FRANCIS	-
Waitaki	1-5	15	-	21	FRANCIS	-
	6-7				Mixed Flow	-
Aviemore	1-4	60	-	37	FRANCIS	-
Benmore	1-6	90	-	105	FRANCIS	-
OhauC	1-4	53	-	-	FRANCIS	-
Manapouri	1-7	84	-	178	FRANCIS	-
Monowai	1-3	2	-	48	Hor. Fran.	-
Highbank	1	27	-	104	FRANCIS	-
Cobb	1-4	3.3	-	594	PELTON	-
	5-6	10.4	-	584	PELTON	-

Note: information on South Island dams is not incomplete.

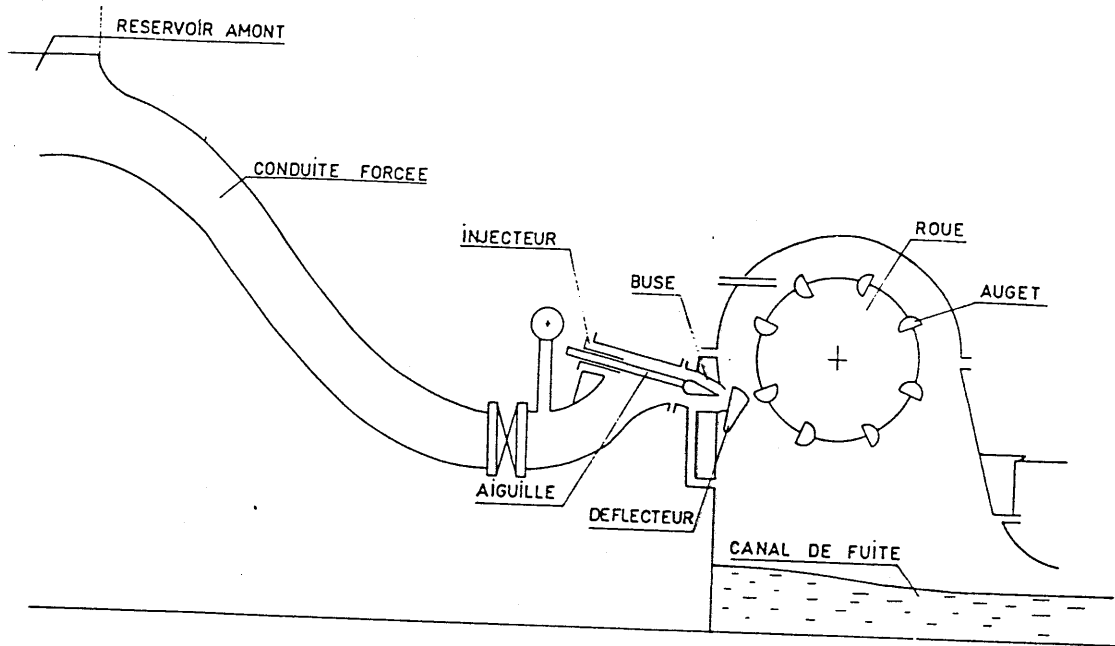


Figure 2. Pelton turbine.

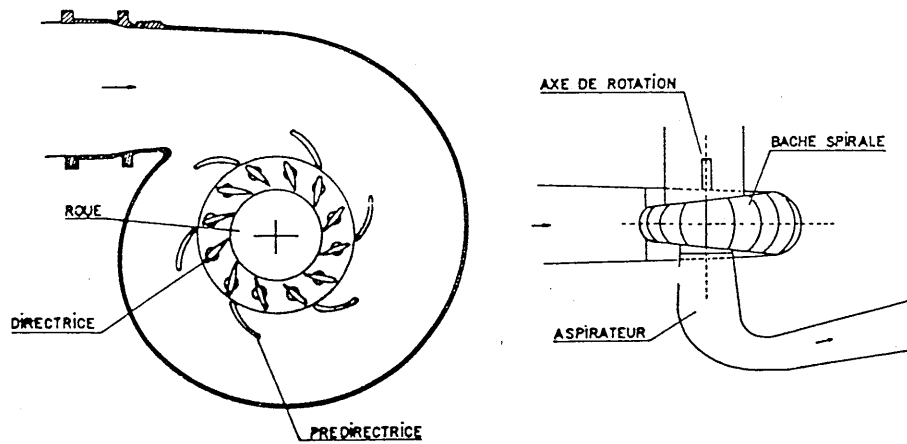


Figure 3. Francis turbine.

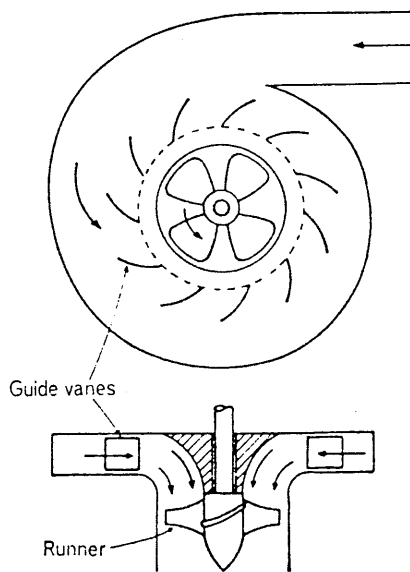


Figure 4. Kaplan turbine

2. Evaluation of methods used for determining impact of turbine passage

It is not easy to evaluate the impact of turbine passage on fish. Observing fish within an operating turbine is impossible, and interference with normal operation of the facility is unlikely to be tolerated. Models and test facilities suffer problems of scale. Virtually all the studies reported in the literature have used the 'black box' approach. Fish are placed in the intake area, or are allowed to migrate naturally through the turbine. They (or parts thereof) are then recaptured downstream and examined or tested for mortality. There can be flaws, as wild fish resident below the dam may be captured and assumed to have survived turbine passage.

A variety of techniques has been employed on the problem:

(i) for species such as salmon, marking and releasing of juveniles above and below the power station then determining return rates of adults have been used. In rivers such as the Columbia in the USA, there are dedicated fish screening and handling facilities for downstream migrants, and it is also possible to determine mortality rates from recaptures made at dams further downstream;

(ii) confining fish in a container that can be retrieved after passage (some bias is introduced by the confinement);

(iii) release of fish in the intake and recapture by netting at turbine outlets (45-95% retrieval rate). Because fish may escape the intake, released fish are usually anaesthetised before release. A criticism of this technique is that use of anaesthetics could bias results. Furthermore, recapture itself is a source of mortality. Mark-release is limited to flows of $100 \text{ m}^3\text{s}^{-1}$ or less. Air and water temperatures are also important as they affect mortality. Tests can be undertaken only when there is little debris in the water, because debris can result in high mortality in the net and damage to the sampling gear. Control tests are required to determine the death rate due to collection (this can range as high as 39-85% for sensitive species, to less than 0.5% for the more robust);

(iv) radio tagging of fish released in the intake. However, tag retrieval was low, and it was difficult to even locate the tagged fish;

(v) use of a floater and weight attached to fish, which allows recovery at the water surface below the plant. This method probably introduces some bias, but the "HI-Z Turb'N" tags (Appendix I), which were developed recently by RMC Environmental Services overcomes this problem. This ingenious tag, about 1 cm by 0.4 cm in size, consists of a small rubber bladder that chemically inflates after about 9 seconds of being triggered. Use of several of these tags on a large fish (eg. eel) would lift the entire animal to the surface (or

portions of it, if cut up during turbine passage). The method has also proved useful for recovering radio tags;

(vi) wideband sonar detection, although not designed to give mortality rate, could permit accurate estimation of the position, number, and size of fish going through intakes. Another use could be for the evaluation of bypass or trapping techniques. This equipment is available (Biosonics, Appendix II), although it is expensive.

2. Mortality due to turbine passage

Fish passing through turbines are subjected to a variety of forces exerted by water flow. The three main forces that damage fish are:

- (a) turbulence and shear across inequalities in water velocity and direction;
- (b) changes in hydrostatic pressure as the water passes through the turbine;
- (c) collision/mechanical contact with turbine components.

At the intake and outlet of a turbine, velocities are rarely above 2 m.s^{-1} . At such velocities little damage to fish occurs, except on the intake screens where, if fish are larger than the apertures, impingement will result. Impingement damage can

range from suffocation by the water flow, bruising, loss of the slime layer, and ablation of skin around the head from attempting to force through the screen. Secondary bacterial and fungal infections are likely to occur in survivors. Impinged fish are often crushed and smothered by debris, and they may be damaged further by the screen clearing process.

Within the turbine, fish are subjected to velocities and pressure changes well above those normally encountered in nature. In a PELTON wheel, velocities are from 50 m.s^{-1} to 150 m.s^{-1} . Pressure can rise in the order of 10's of bars within a fraction of a second. In FRANCIS or KAPLAN turbines, velocity and pressure changes are smaller, but water speeds are still between 6 m.s^{-1} and 40 m.s^{-1} . At these velocities, fish are incapable of avoiding anything. Finally, a pressure drop from several atmospheres at the guide vanes, to atmospheric or even below atmospheric pressure at the outlet, is experienced within seconds.

Turbine design dictates mortality rates. Because of the high forces in a PELTON turbine, the probability of a fish surviving passage is minimal (even if small size allows it to pass through the injection opening without damage). For FRANCIS turbines, fish mortality ranges from 0 to 100%, with a mean of around 37%. Less damage is usually reported for KAPLAN turbines, with values ranging from 0 to 30% (mean 9%), but this probably relates to the fact that KAPLAN turbines are usually installed at lower head sites. Fish mortality at

reduced load is substantially reduced in FRANCIS but not in KAPLAN turbines.

Most studies have shown that mortality increases with the size of fish (Fig 5). The next most significant factor is the speed of rotation of the turbine. Eels, which are large when outmigrating, have a resulting high mortality rate. Published figures for European (*A.anguilla*) and American eels (*Anguilla rostrata*) ranged from 25% to 100% for KAPLAN and 9% to 100% for FRANCIS turbines (Table 1). New Zealand eels, particularly longfinned eels, are considerably larger than European and American eels and so higher mortality rates are expected.

Table 2. Published mortality figures for eel passage through turbines.

Reference	Length (cm)	Mortality (%)
FRANCIS		
Monten <i>et al.</i> 1964	50-52	9-100
Lindroth 1941 & Svärdson 1944	70-80	40
KAPLAN		
Gustavsberg 1960	73.5	91-100
Långgöl 1960,61	73.5	89.8-97.8
	56.5	75-80.8
Karlsnäs 1960	73.5	83-88
Nöbbelev 1960	73.5	72.8-83.8
Emsfors 1960	56.5	63
	73.5	73
Broby 1960	73.5	74-81.2
Kvarnaholm 1961	73.5	51-92
Ängäback 1960	73.5	40-63
Berg 1985	25-82	25-50

The other critical group of migratory New Zealand native fish migrate downstream as larvae. The only work that has been done

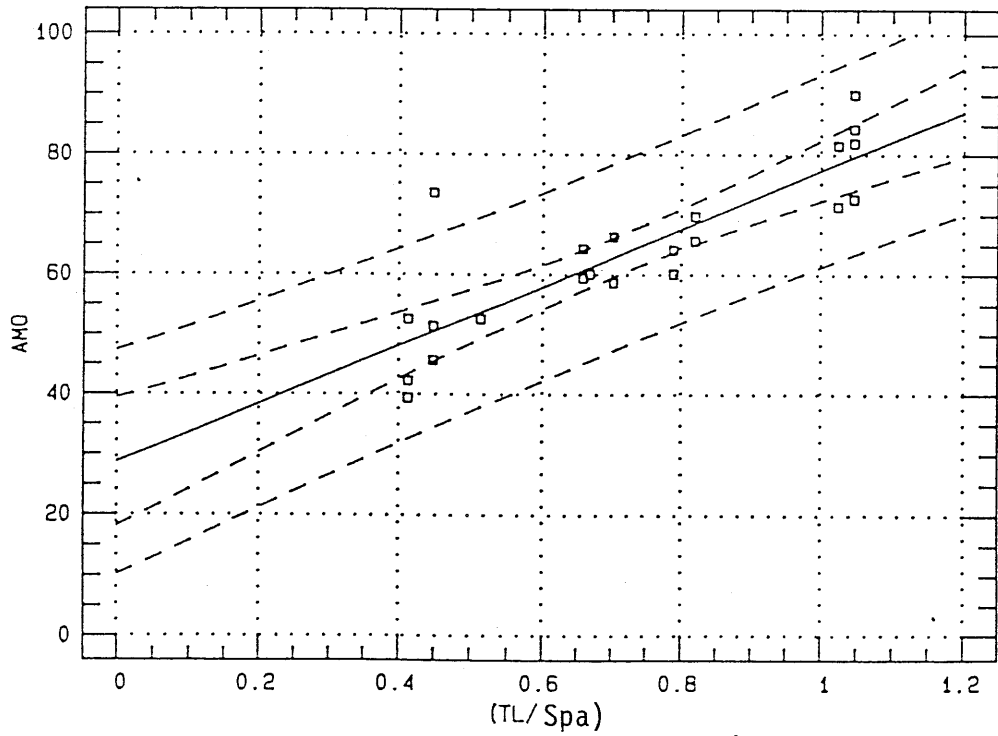


Fig. 5. Relationship of predicted and observed transformed mortalities (AMO) on eels against the variable (TL/Spa). Linear regression on KAPLAN turbines with 95% confidence and prediction limits.

on turbine mortality rates of larval fish is a theoretical review for low head KAPLAN (bulb) turbines by Cada (1990). His conclusion was that less than 5% of entrained ichthyoplankton would be affected. Most of the other studies on small fish were for juvenile salmonids. Once the more obvious and pressing problem of migrant eel passage is solved, studies should be done on native fish larvae.

2. Types of damage inflicted upon fish during Turbine Passage

Examination of fish after turbine passage has resulted in identification of the following types of damage:

(i) Mechanical (due to contact with fixed or mobile parts of the turbine).

This results in cuts to various parts of the body and internal bleeding. An important factor for survival of fish is the velocity of the water in relation to the turbine. In FRANCIS turbines this velocity differential can vary from 4 m.s^{-1} to more than 20 m.s^{-1} . It decreases significantly with opening of the guide vanes (or as the turbine speed increases). In a KAPLAN, the differential can vary from 7 m.s^{-1} to more than 30 m.s^{-1} , but changes relatively little with opening. For KAPLAN, velocity near the axle is lower than on the outer edge of the blades, and fish are subjected to different forces depending on what area of the turbine they pass through.

(ii) Effects of rapid pressure change.

This varies from simple punctures (notably of the eye) to a complete blowing apart of the body. Pressure changes also cause internal bleeding, air embolism, and rupture of the swim bladder. Pressure effects are partly dependent on pre-adaptation (i.e., the depth at which the fish was swimming before entrainment), and on the species. The effect is usually limited, as long as pressures remain within 50-60% of the acclimation pressure.

(iii) Shearing effects (due to changes in velocity within the length of the fish).

Shear is a major concern, particularly for long-bodied fishes such as eels. Shear causes distinct injuries (torn opercula, inverted gill arches, and decapitation) as the head and body are pulled violently in different directions. Commonly, the result is that the gill covers are opened with sufficient force to tear the head off.

(iv) Turbulence

Turbulence affects fish because differences in water speed and direction within the turbine chamber and draft tube suddenly alter the course of a fish's passage. Turbulence causes injuries such as contusions and abrasions. Severe turbulence results in shredding (due to multiple passage of the fish in a

turbulent zone or across areas of differing velocities). The frequency of shredded fish can be as high as 36% in KAPLAN turbines, but was found to be only 1.6% in FRANCIS. However, deaths due to less obvious causes were up to 62% on FRANCIS and only 18% in KAPLAN.

(v) Cavitation

Cavitation can occur in turbines operating at high loads. Waves of low pressure develop at the leading edges of the blades. Bubbles form in this process and collapse as they are forced to regions of high pressure, resulting in local shock waves. Experiments using model turbines found that induced cavitation increased fish mortality rates at normal running speeds by 52-93% for FRANCIS and 66-85% for KAPLAN turbines.

2.5 Principal causes of damage in different turbine designs

With KAPLAN turbines, the higher the turbine intake velocity, the greater the mortality. Mortality also tends to increase at low efficiencies and with increasing height of the turbine above the tail race (suction effect). The angle of opening of the guide vanes, although apparently not affecting overall mortality, does affect the type of damage sustained. For example, at 75% opening (maximum efficiency), internal bleeding is the primary cause of mortality whereas at 100% opening, separation of the head from the body can comprise 29-49% of deaths recorded. Pressure changes account for only 2%

of immediate mortalities.

For FRANCIS turbines the most important factors tend to be:

- (i) increase in head;
- (ii) drop in hydraulic efficiency;
- (iii) cavitation;
- (iv) clearances between the runner and guide vanes;
- (v) high rotation speed (common on smaller turbines).

3. PREDICTIVE MODELLING

Until recently, predictive work on mortality caused by turbine passage has been largely site specific. For FRANCIS turbines, the most significant components were reported to be the opening of the vanes, Thoma coefficient, cavitation, and length of fish. For KAPLAN turbines, square root of the fall and Thoma coefficient have been the most significant factors noted (Davies 1988). Von Raben (1957) produced the first generalised equation for estimation of the percentage eel mortality on passage through KAPLAN turbines.

Lately, Larinier and Dartiguelongue (1989) have used both turbine characteristics and operating conditions in much more elaborate predictive modelling. They reviewed the published data and conducted a series of experiments. Their results are notable for gruesome coloured photographs of fish after turbine passage.

For FRANCIS turbines, these authors found that the most significant factors were: absolute velocity at the entry to the turbine, and a group of components which included the relative velocity of the turbine, the size of the fish, the space between the runners, and, to some extent, rotation speed. They also considered that absolute velocity was related to fall, but noted that this conclusion was not consistent amongst workers. For KAPLAN, the important factors were length of fish and distance between the blades (obviously the chances of a fish passing through the turbine without collision with the blades will depend upon the length of the fish and the distance between successive blades). However, they did note that the data set they used was not complete due to lack of information on some installations. They mentioned Berg's (1986) work on eels which showed that mortality was related to the angle of the blades at entry (mortality increased significantly as the blades closed).

The best formulae derived by Larinier and Dartiguelongue (using the ARCSIN square root transformed mortality rate (AMO) were:

FRANCIS:

$$\text{AMO} = -4.21 + 1.25 V^{0.821} + 2.28N^{0.19}(\text{TL}/\text{Spa})^{0.84}W^{0.71} \\ (\text{R}=0.87)$$

KAPLAN:

Trout
 $\text{AMO} = 10.6 + 53(\text{TL}/\text{Spa}) + 0.083\text{Pow} \quad (\text{R} = 0.65)$

Eel
 $\text{AMO} = 28.6 + 48.7(\text{TL}/\text{Spa}) \quad (\text{R} = 0.85)$

All species

$$AMO = 12.2 + 72.7(TL^{1.125}/Spa^{0.843}) \quad (R = 0.97)$$

where:

- V1 = Absolute velocity at entry of turbine
- N = Rotation speed
- Nor = Number of runners or blades
- TL = Total length of animal
- Spa = space between runner and blades = $\pi D1m/Nor$
- W1 = Relative velocity at entry of turbine
- Pow = Power in MW
- D1m = Diameter of turbine taken at 1/2 runner height for FRANCIS and 1/2 blades for KAPLAN

4. MORTALITY RATES FOR EELS IN NEW ZEALAND

The primary question of this review is: what is the magnitude of the impact of turbine passage on downstream migrating fish in New Zealand ?

We used the formulae of Larinier and Dartiguelongue (1989) and collated the relevant variables for both Karapiro and Matahina (Table 3). These two dams have good stocks of eels in their reservoirs. Karapiro has Kaplan turbines and Matahina has Francis turbines.

We estimated that mortality for an average size downstream migrant female shortfinned eel (750 mm) would be 90.6% at Karapiro (KAPLAN) and 46.9% at Matahina (FRANCIS). Longfinned migrant females, which are much longer (1150 mm), would suffer mortalities of 100% and 75.5% respectively. For 100 mm lamprey juveniles migrating downstream, mortality was predicted to be 32% at Karapiro and 3.8% at Matahina. Estimates for Karapiro use the "Spa" value provided by Electricorp mechanical section.

Table 3. Turbine variables needed to calculate fish mortality rates.

	KARAPIRO	MATAHINA
Type	KAPLAN	FRANCIS
Diam. runner	4.337 m	3.048 m
Speed	167 rpm	128.6 rpm
No. of blades	5	15
Power (HP)	42000	50000
Space (Spa)	0.833 m (Max)	0.638 M
V abs (V1)	14.8 m.s ⁻¹	9.54 m.s ⁻¹
V rel (W1)	20.0 m.s ⁻¹	12.5 m.s ⁻¹

Dartelongue and Lariner provided the following formula for calculating Spa:

$$\text{Spa} = \pi \cdot D1m / \text{Nor}$$

$$\text{For KARAPIRO} = \pi \cdot 4.337 / 5 = 2.725$$

This formula is not really a method for calculating the spaces between the blades at all. Rather it is a multiplier which allows the number of blades to be considered. A large turbine with fewer blades would give higher Spa values than a small multibladed turbine. Thus, "Spa" represents the probability of a fish encountering a leading edge during passage.

Recalculation of AMO for Karapiro, using this formula for Spa and disregarding the true value, gives 44.8% mortality for migrant female shortfinned eels and 57% mortality for female longfinned eels. The estimated mortality for lampreys also falls to 25%.

Regardless of the formulae and which value is most correct, it is obvious that there is probably significant mortality of downstream migrating eels at hydro-electric facilities in New Zealand. Larger eels and longfinned eels (both of which predominate in upstream habitats) would be most affected most seriously. The impact flows on to the productivity of the species. Large fish produce more eggs than smaller individuals of the same species. Tesch (1977) provided an equation to calculate the fecundity of eels:

$$\log \text{ EGGS} = -4.2951 + 3.74418 \log \text{ LENGTH}$$

Thus it can be calculated that a large migrant female longfinned eel (1500 mm) can produce nearly 40 million eggs whereas a small female longfin (800 mm) has a reproductive output of less than 4 million eggs. The need to maximise reproductive output is emphasised by rising concern that present commercial fishing pressure is too great to allow significant survival of female eels to the age of maturity.

5. METHODS AVAILABLE TO PREVENT EELS FROM BEING KILLED BY TURBINES

The only practical means of decreasing mortality due to turbine passage is to prevent eels from entering the turbine intake. There are three alternative approaches:

1. shutdown and spillage of water;

2. fish screens;
3. behavioural devices to repel migrants from the intakes.

The simplest solution would be to stop generation and divert fish to an open spillway. This may be the most cost-effective method, because there are only about nine nights in the year, in late summer, to be considered. Unfortunately, the migration of eels is probably synchronous throughout New Zealand. If the plant must continue generating, then collection and release of migrants downstream has to be considered.

5.1 Fish Screens

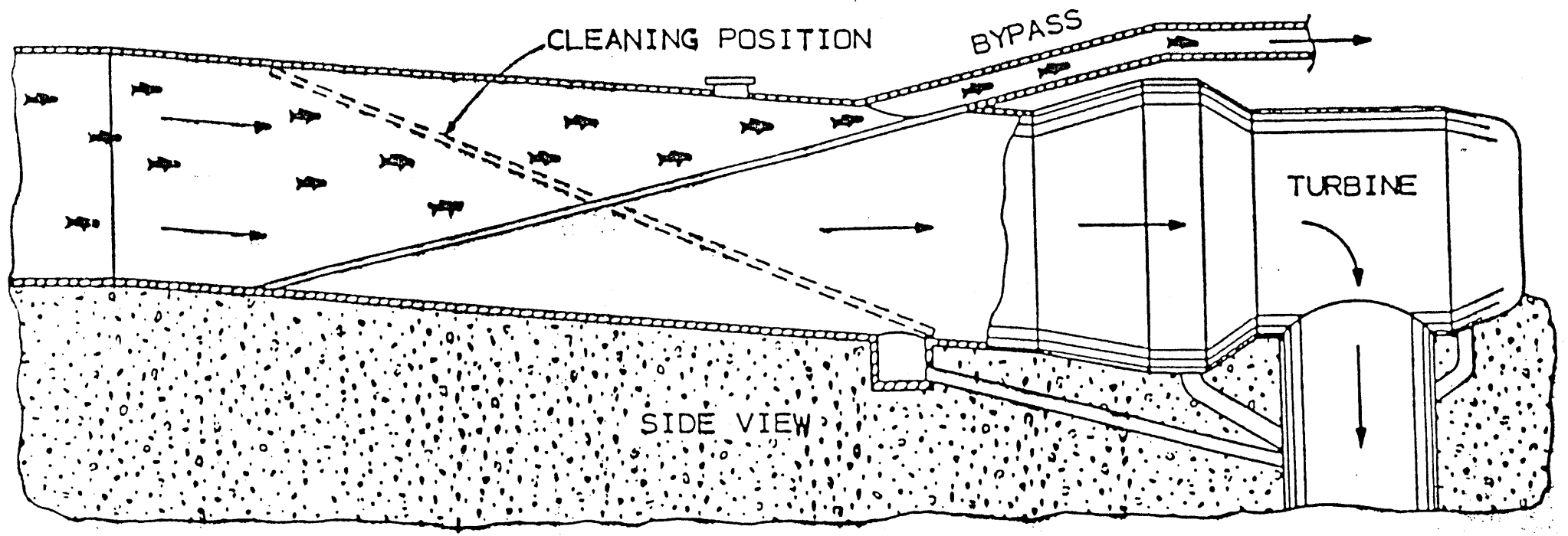
Trash screens are already fitted to Electricorp facilities, but the bar spacings observed by the authors are too wide to exclude migrant eels. However, Aniwhenua operates 30 mm spaced trash screens (the recent invasion of water net has caused some problems). Trash screens are always mounted over the penstock intakes, giving them a small effective screening area and resulting high water velocities. Although large migrant eels are screened out of the turbines at Aniwhenua, they are still impinged on the screens and killed. For effective fish screens, the aim is to have water velocities below 0.12 m.s^{-1} prevent fish impingement (criteria used in the USA are given in Appendix III). The following screens have been designed to exclude fish:

(i) Eicher screens (Fig. 6)

These screens are set at an angle across the penstocks, permitting a longer (bigger) screen to be fitted. This reduces flow rates and allows smaller bar gaps. The method has been claimed to have great potential for protecting downstream migrants. A fish collection point is formed at the downstream angle of the screen. Relatively low construction costs and low maintenance and operation costs (they can be made self-cleaning by tipping) are held to be the major advantages of Eicher screens (see Eicher 1981, Adam *et al.* 1990 and Winchell and Sullivan 1991).

(ii) Submerged travelling screens (Fig. 7)

Eels probably migrate surface water layers (Tesch 1977, commercial eel fishermen pers. comm.), as do the majority of salmon smolts. For salmon smolts, submerged vertical travelling screens that extend approximately 1/3 of the way into the turbine intake have been fitted at facilities like Bonneville dam on the Columbia River, USA. These screens are made of nylon or steel webbing, and are not intended to screen all the turbine flow, but to collect fish in the upper water layer only. Fish are diverted upward into emergency bulkhead slots, and then pass through an orifice into a collection gallery. For older dams that are being retrofitted with similar screens, tunnels have had to be dug. The water (and fish) are then discharged downstream of the dam (for dams



Pressure wedge-wire screen in turbine penstock

Figure 6. Eicher screen.

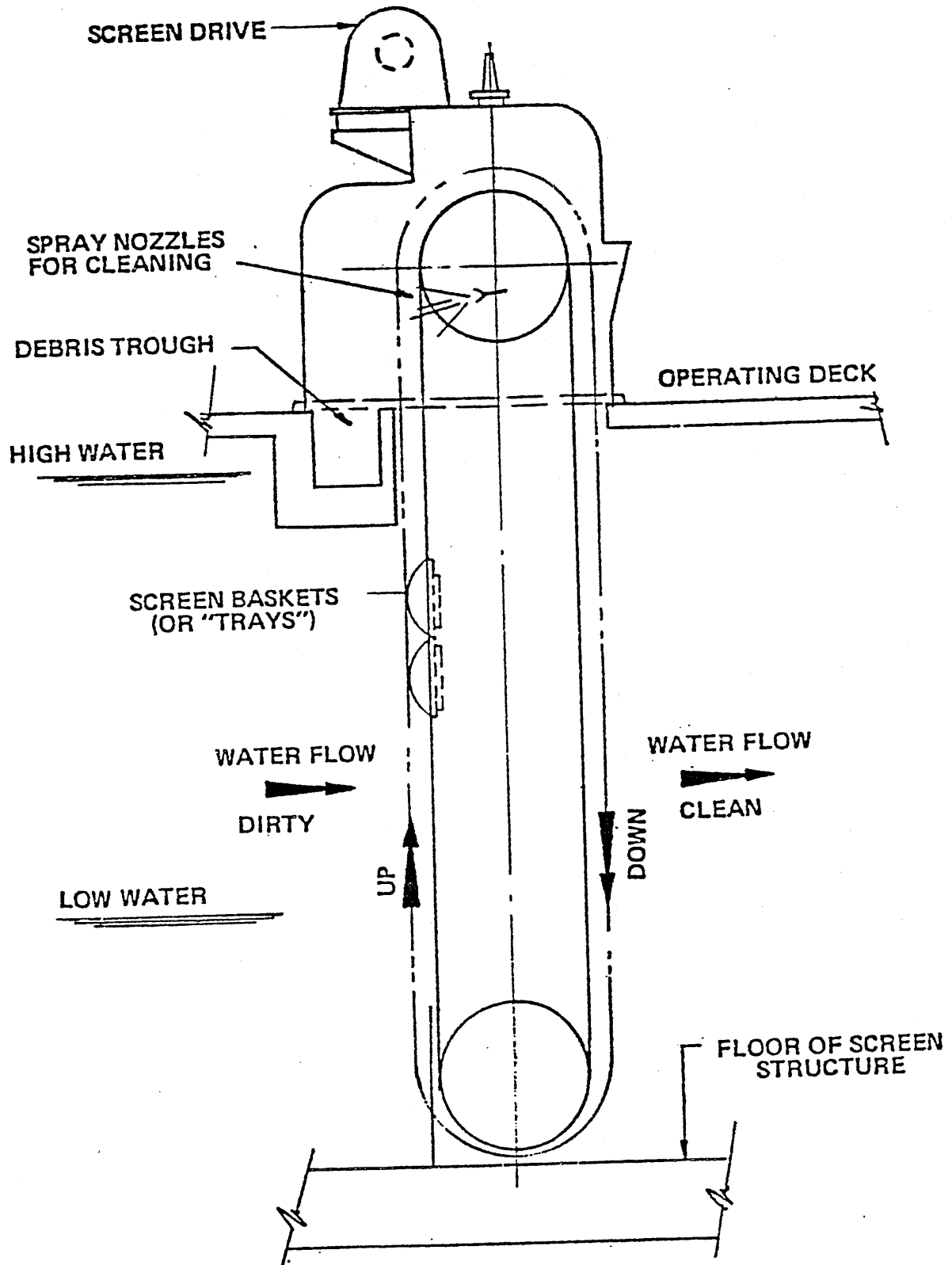
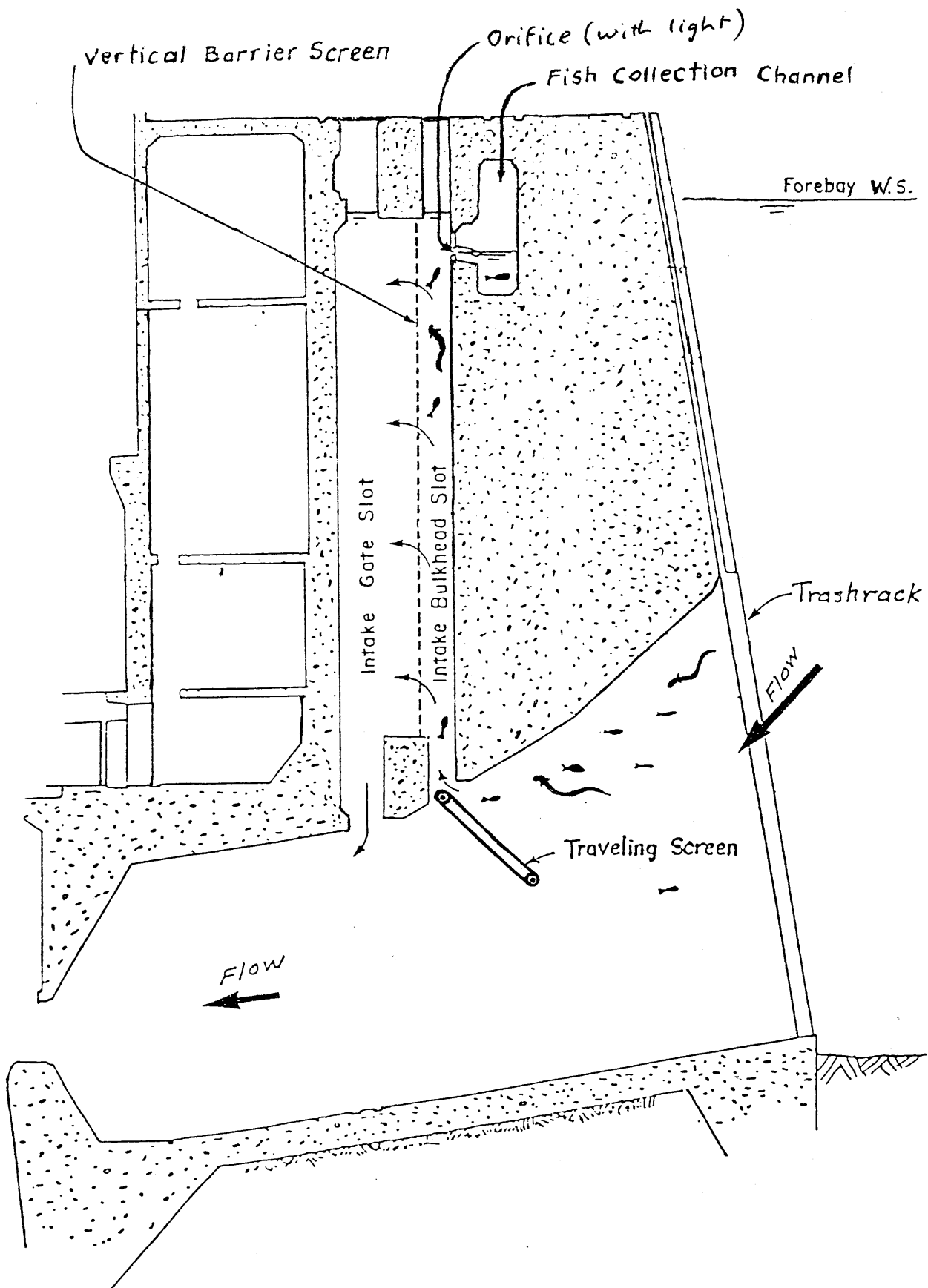


Figure 7. CONVENTIONAL VERTICAL TRAVELING SCREEN



Schematic drawing of traveling screen placement

Figure 7 (Continued...) Submerged travelling screen

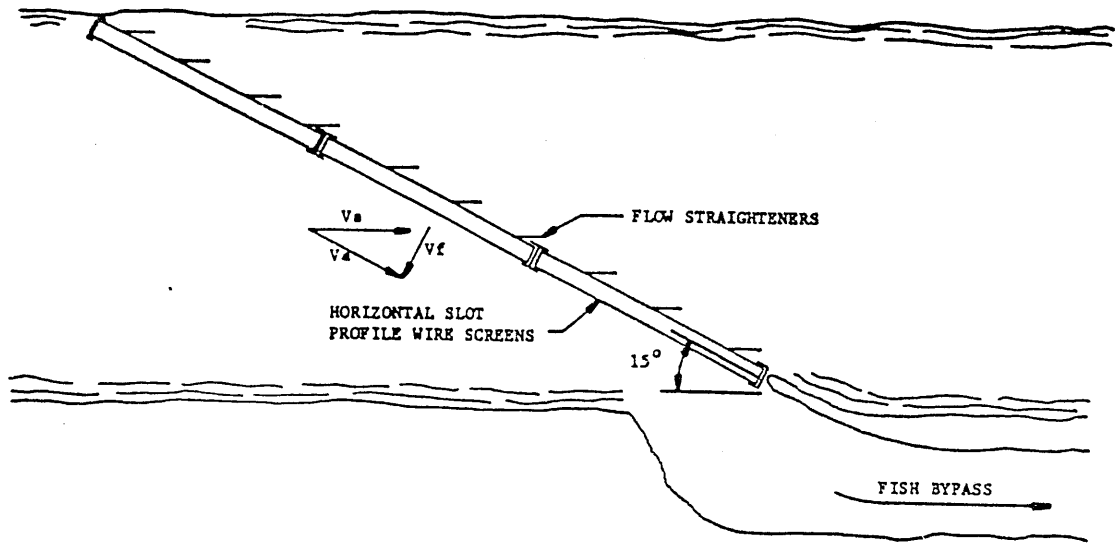
higher up the river, barges and tanker trucks are used to take fish below the lowest dam). At the time of a recent MAF-funded study tour of the USA (by JAB), studies were underway to determine longterm survival of fish after passage.

(iii) Passive screens (Fig. 8)

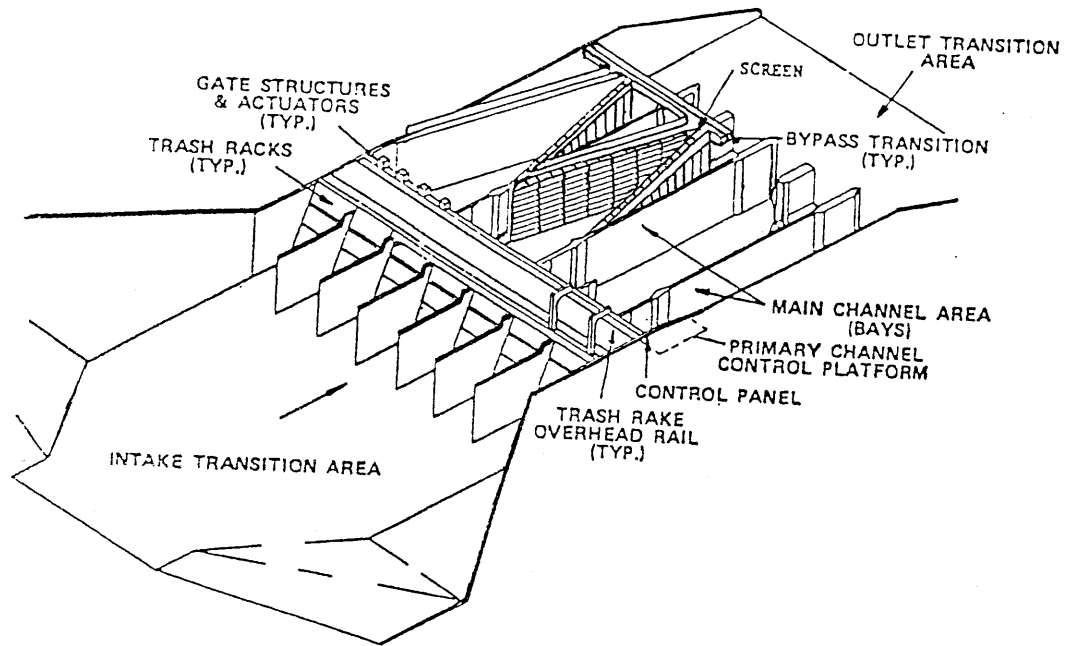
In-river, passive, inclined screens usually consist of perforated stainless steel plate with continuously operating brush cleaners, a training wall and angled trashrack. Theoretically, the concept was theoretically ideal for fish, but in reality, there have been major problems (trash rack failure and heavy damage to screens in floods).

(iv) Drum screens (Fig. 9)

This type of screening is usually found on irrigation intakes but has been used for smaller power plants. One such fish protection system on the Chandler irrigation and hydropower diversion project in the Columbia basin ($42 \text{ m}^3 \cdot \text{s}^{-1}$) consisted of 24 rotary drum screens, each 5.4 m diameter and 5 m long, with three bypasses and a series of secondary vertical travelling screens with pumpback capability (to use water from the bypass flow). Although the design is very different, our experience at Huntly with drum screens has not been good. Migrant eels in particular suffered heavy losses from these screens (Palmer *et al.* 1987).



Simple fish diversion system



Intake channel fish diversion screen

Figure 8. Passive fish screens

Required Design Improvements Improvements compared to older drum screen designs were numerous. New designs included 0.75-1.0 horsepower motors (for rotary screens) mounted directly on each drum screen frame, replacing paddlewheels. Drive chain and sprocket housings (partially filled with oil) were designed to allow reduced wear compared to older systems, which allowed drive chains to be submerged in the canal. Training walls were incorporated for each bypass to improve fish guidance. Pier noses were shaped to match the curvature of the upstream face of the drum screen, thereby allowing juveniles tracking near the angled screen bottom seal to move unimpeded toward the bypass, as shown in Fig. 2. Improved side and bottom seal designs have reduced entrainment under and around each drum screen to negligible levels. Use of stainless steel mesh has reduced maintenance and increased longevity.

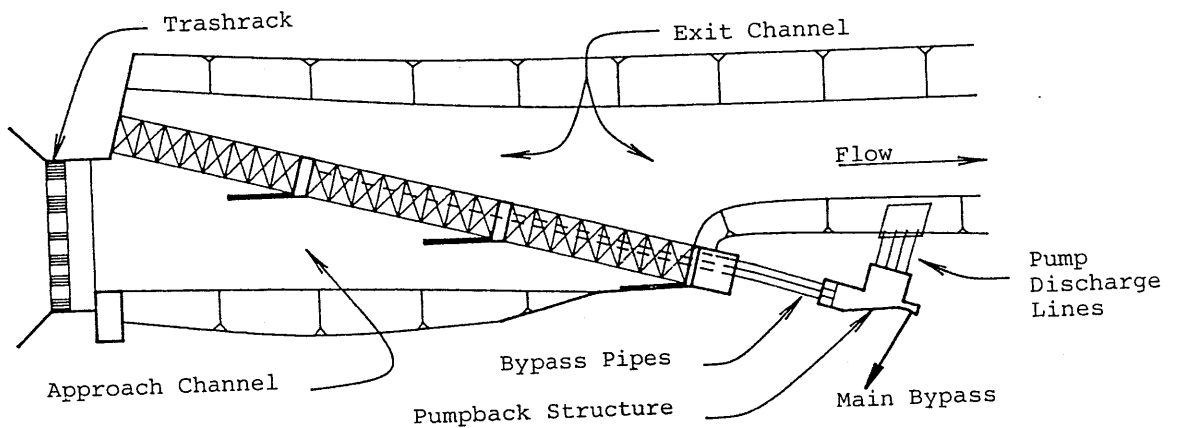
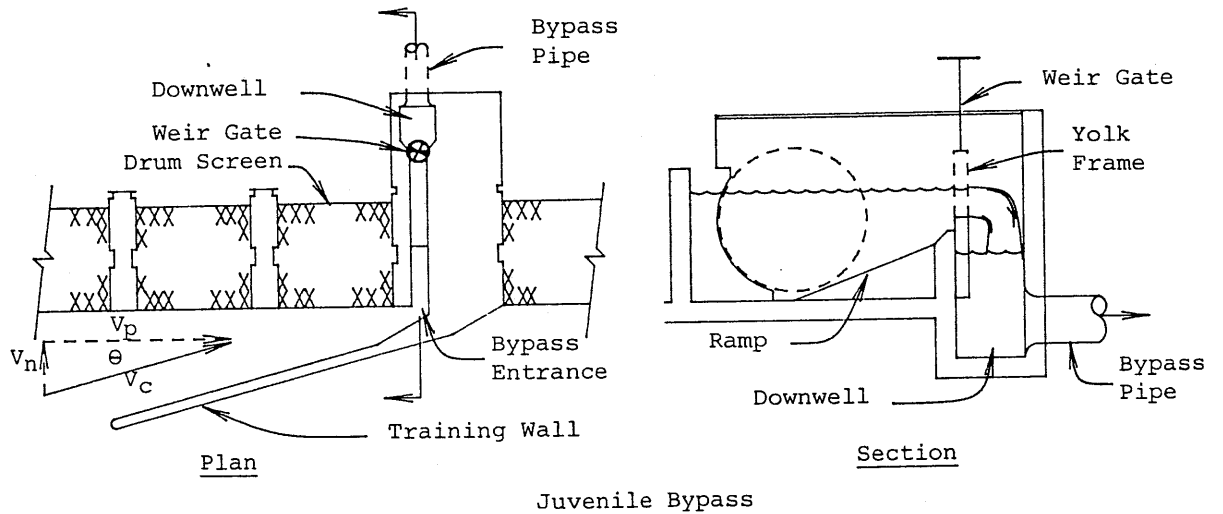


Figure 9. Drum screens (from Rainey 1990)

(v) Wedge-wire screens (Fig. 10)

Vertical, passive screens (wedge-wire) are fine-meshed slot screens, which usually require some sort of cleaning system. Designs capable of screening-out fish larvae have been proposed for New Zealand (minutes of the Waikato Thermal Power Station investigations group). Although effective, they are possibly one of the most expensive systems available. The cost of installing wedge-wire screens for a $22 \text{ m}^3 \cdot \text{s}^{-1}$ intake in America was approximately US\$2.5 million (1 MW output).

(vi) Fish transfer systems

Instead of operating a bypass, which implies spilling potential generation capacity to pass downstream migrants, cheaper options have been sought. One solution is to concentrate and then pump fish over the dam. Hydrostal pumps have been used to transport eels (Patrick and Sim 1985, Patrick and McKinley 1987), but mortality can be high for more delicate fish (Rodgers and Paul 1985). Active and effective avoidance of the pump intake also occurs. Therefore lights have been used to attract fish to the pump intake, and clear plastic intakes used to reduce avoidance (Christie 1990).

The usual finding has been that fish have to be confined within a limited space before they can be captured by these relatively low-powered pumps. This has been achieved by using a fish collection sump which is periodically dewatered by the

pump (Christie 1990, Konagaya 1990). However these studies used upstream migrants.

The response of migrant eels, which are deliberately moving downstream, might be to accept and move toward a fish pump intake. If this was shown to be the case, then a fish pump in conjunction with an angled screen could prove an effective bypass system.

5.2 Intrusion into turbines

In addition to problems for downstream migrants, upstream migrating fish can be attracted to, and will enter, stopped turbines. On restart, heavy mortality can occur. There has been some success in preventing this by constructing well-designed drop structures. In all cases, however, a fall of at least 2 m was required and this is not an option at most existing power plants. A loss of generation potential is also implied. Thus, the only effective protection measures that could be taken are to screen the turbine outlet, or, possibly, to use behavioural barriers such as electric fields or lighting (Patrick *et al.* 1982).

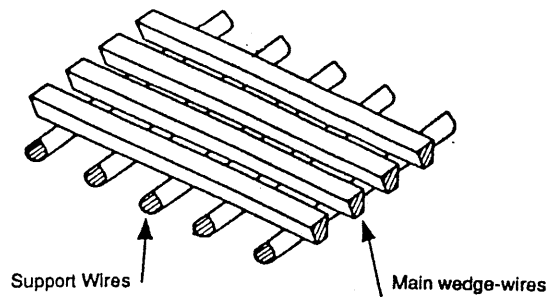
5.3 Behavioural methods for excluding fish from turbine intakes

Behavioural methods are appealing. They are unlikely to involve expensive modifications to existing structures, and,

unlike screening systems, they do not interfere with hydraulic efficiency. Behavioural methods need only function when the fish are actively migrating, which gives the potential to greatly increase service lifespans. For these reasons, a variety of systems for repelling fish from intakes has been designed and tested.

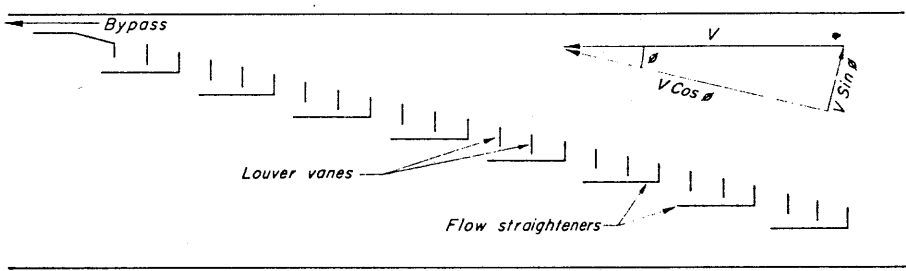
(i) Louvres (Fig. 11)

Louvres comprise a series of vertical slats placed in a diagonal line across the migratory path of downstream migrating fish with each slat placed at right angles to the direction of flow. Upon approaching the slats, fish tend to avoid them while continuing downstream, and thus are guided to a bypass at the downstream end of the louvre line. Ruggles (1990) considered that louvres are the only behavioural fish screening technique that have proven effective in removing fish from turbine intakes. "They appear most suited for diverting migratory species during the time of their seaward migration". At Hadley Falls (Connecticut), a combination of a floating louvre array and surface spills over the ice and trash sluiceway was used to divert salmon smolts and juvenile shad. A prototype screened the top 2.4 m of the water column. The slats were polypropylene strips, 6.4 cm wide at 7.6 cm centres, the array intercepting the flow at an angle of 15° . Tests found that 80% to 100% of fish released into a 44 m wide canal were guided into a 4 m gap at the downstream end of the array. Approach velocities were from $0.2 - 1.0 \text{ m}\cdot\text{s}^{-1}$.



A section of stainless steel wedge-wire screen

Figure 10. Wedge wire screen



V = Approach velocity of water in flume
 θ = Angle of line of louvers
 $V \sin \theta$ = Swimming velocity of fish
 $V \cos \theta$ = Resultant velocity of body of fish

Figure 11. Louver screen and the underlying geometry.

(ii) Electric fish barriers

Electric fish barriers consist of a charged field across a waterway. They have proven useful in some locations for upstream migrating fish, but have never been successful for downstream migrants. Carried by the current, fish tend to be swept through the field, even at field strengths which interfere with neuromuscular function. Nevertheless, one author (CPM) has the opinion that electrically-charged mechanical fish screens, with head width bar spacings, could be particularly repellent for migrant eels. The length of these large fishes ensures a good voltage drop as they approached the screens, thus electricity would be effective at low field strengths. Charged screens using low frequency pulsed DC, with short pulse durations (eg. 100 microseconds/5 pulses per second, 20-40 milliamperes), would be effective but safe for humans. The use of low-wear plastics as screen guides would give insulation of the screen from the surrounding dam structure.

But, use of electricity would only be an adjunct to suitable mechanical screens. Electricity could only be used to stop impingement and help divert fish toward a passage facility. Electrification of existing trash racks would not be a suitable approach as through-screen water velocities need to be greatly reduced.

(iii) Low-frequency sounds

Sound generated by pneumatic poppers (a modified seismic

device which emits low-frequency, high intensity sounds) has been shown to repel adult alewife in North America (Haymes and Patrick 1986). A subsequent design, with lower maintenance requirements, is the 'fishpulser'. This is a spring-mass impact device which can generate a repetitive, high amplitude, 'sharp' sound from between 20 -1000 Hz. Three of these devices in front of a turbine intake resulted in over 70% of the *Alosa pseudohaerengus* (a herring) migration being diverted to a bypass 40 m away. However, the method may not be effective for other species (or smaller fish), and may even attract predatory species such as eels. Kynard and O'Leary (1990) gained only a temporary inhibition of the downstream migration of shad using an acoustic field generated by scanning sonar.

(iv) Air bubble curtains

Patrick *et al.* 1982 have shown that, under laboratory conditions, a combination of strobe light and air bubbles can divert fish. It is known, however, that some demersal species are attracted to an air bubble curtain. We could not find any reports in the literature where the system had been tested rigorously under field conditions.

(v) Light

Eels migrate during darkness, and even moonlight reduces their activity. Lights have been used successfully to deflect eels toward traps (Lowe 1952, Nolan *et al.* 1986), and also have been used to reduce mortality at power station intakes (Haddingh 1979). Silver eels (which are committed to

migrating downstream) are most sensitive to the blue-green end of the spectrum. Unfortunately, that is precisely the hue which is most affected by turbidity, so use of the method may be restricted to clear or shallow waters. A strobe light with a flash power of approximately 1 watt, a flash duration of about 80 microseconds, and a spectral range of 400-700 nm has been shown to cause avoidance reaction in some fish species and eels (Patrick *et al.* 1985).

Strobe lights have been used successfully used to prevent American eels migrating into turbine tubes during shut-downs (Patrick *et al.* 1982). Salmonids appear to be repelled by strobe lights, but, conversely, other fish have been attracted, because, from a distance, strobe lights may appear as a constant light source.

The use of light, notably strobe light, could be a promising behavioural means of excluding eels from intakes. However, like other behavioural systems, avoidance is likely to be lessened when current velocities are greater than 0.32 m.s^{-1} . Furthermore, lights have been employed to attract some species (notably towards fish passing facilities) (Haymes *et al.* 1984, Rodgers and Patrick 1985), and problems may occur with species such as smelt in New Zealand.

6. DISCUSSION

Because of their size, it appears likely that downstream migrating eels suffer a high rate of, if not total, mortality

during turbine passage. Little can be done to turbines to alleviate this problem. A simple solution is to shut down those stations with an eel problem on the few nights of the year when most migration occurs. Eels can then follow the flow over the spillway to make their escape.

If generation has to be maintained, then fish must be prevented from entering the turbines. Obviously, the only totally effective method of excluding eels from penstock intakes is by full screening, but existing screens that exclude eels still kill them. Satisfactory screening may be both difficult and expensive for existing installations. In addition, the migrants remain trapped within the reservoir.

The first problem is to stop eel migration into the turbines, and then to physically remove them from the reservoir. Migrant eels are committed to travelling downstream, and anything blocking this instinctive migration will be challenged continually until an alternative passage (i.e., water spillage) became available. Unless an analysis of spillway gate opening, rainfall, and eel migration periods shows that opportunities for escape over spillways are frequent during the migration period, then eel migration will be adversely affected, even at screened hydro-dams.

Vertical travelling screens that divert fish from part of the intake may be effective for eels, as there are indications that they travel within the top 1-2 m of the water column

(hydro-acoustics could help to determine this). Eicher screens also show promise, both in terms of construction and operating cost. Implicit with screening is a commitment to bypassing the migrants downstream. Note that fish handling systems will have their own construction, operation, and maintenance costs.

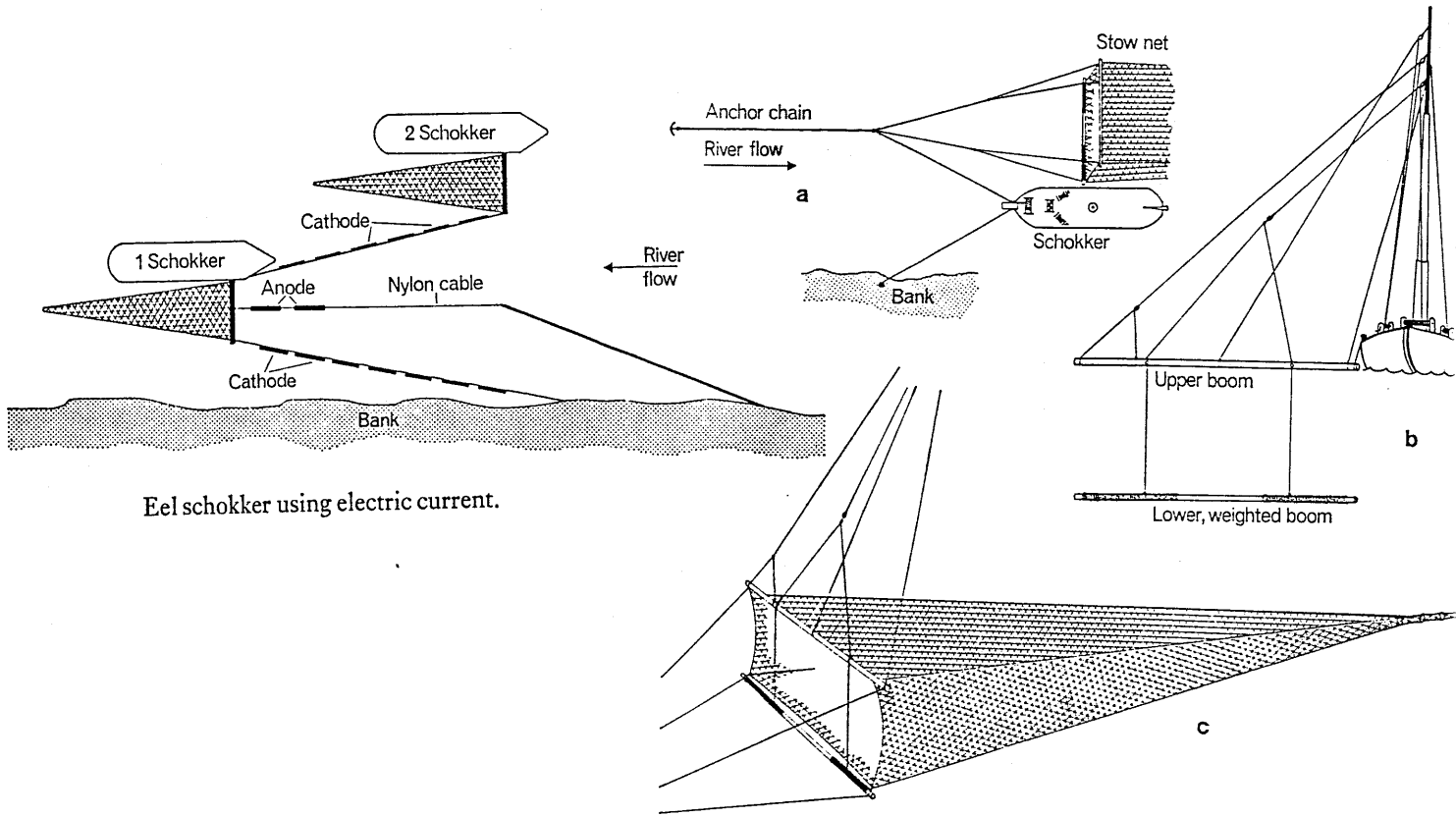
Behavioural systems to divert fish from power station intakes are initially more attractive than physical barriers, because they cost less to install and maintain. Repulsion by strobe lights appeared to work on some downstream migrants and louvred screens may have potential for diversion of eels away from the intake area. Other behavioural methods, such as electric fields, could be considered to protect upstream migrants. However, apart from experimental installations, we could find no reference to the successful use of behavioural systems as part of fish protection commercial generation facilities.

We recommend that, in the first instance, trials be undertaken to deflect downstream migrant eels towards the shorelines, using light or a combination of light and louvres. It is thought that eels naturally approach lake outlets down the sides of the lakes. If a light avoidance/louvre system proved successful, eels could be deflected towards a bypass or towards traps. Trapping of migrant eels (tunaheke) was traditionally a major fishery for inland ⁻¹maori. In Europe, there are specialised silverbelly eel fisheries in recognition of the excellent flesh quality of migrants. Every season,

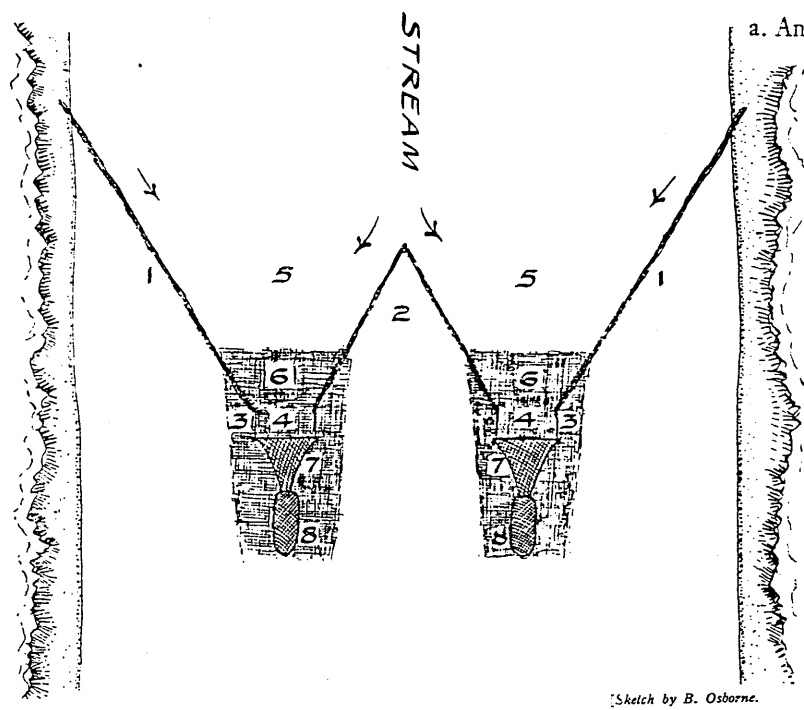
large numbers of elaborate trap nets are worked in rivers (Fig. 12) and the Baltic sea (Tesch 1977).

Based upon a mean productivity of only $20 \text{ kg}\cdot\text{ha}^{-1}$, it can be estimated that a stock of eels worth around \$60,000 may migrate from Karapiro alone over a few nights every year. If MAF Fisheries could develop a trapping system which was compatible with dam operational requirements, and generated a profit, then public interest would be intense. It also would be useful to Electricorp if the process of removing migrant eels was self-funding and self-organising. The system could be operated either by Tangata Whenua or by commercial fishers under license. The method would obviously require a proportion of the catch to be released below the lowest dam in return for the right to operate the traps.

A compensation policy like this also is compatible with traditional Maori values. A Ngai Tahu document dealing with Maori environmental management systems (Tau *et al.* 1990) described deliberate release of small 'male' eels and the very large 'females' (Pou tuna). As fecundity or egg output in fishes varies with length raised by a power, this is good practical fisheries management, optimising fish harvest as well as egg production from the catchment.



a. Anchoring system. b. Connections between vessel and gear. c. Stow net.



A pa taurenu having two ngutu, as used in taking eels moving down-stream. 1, paihau; 2, tuki; 3, tapangutu; 4, ngutu; 5, waha; 6, whakareinga, whakatukapau, whariki (scour-mat); 7, purangi (leading-net); 8, hinaki (eel-pot).

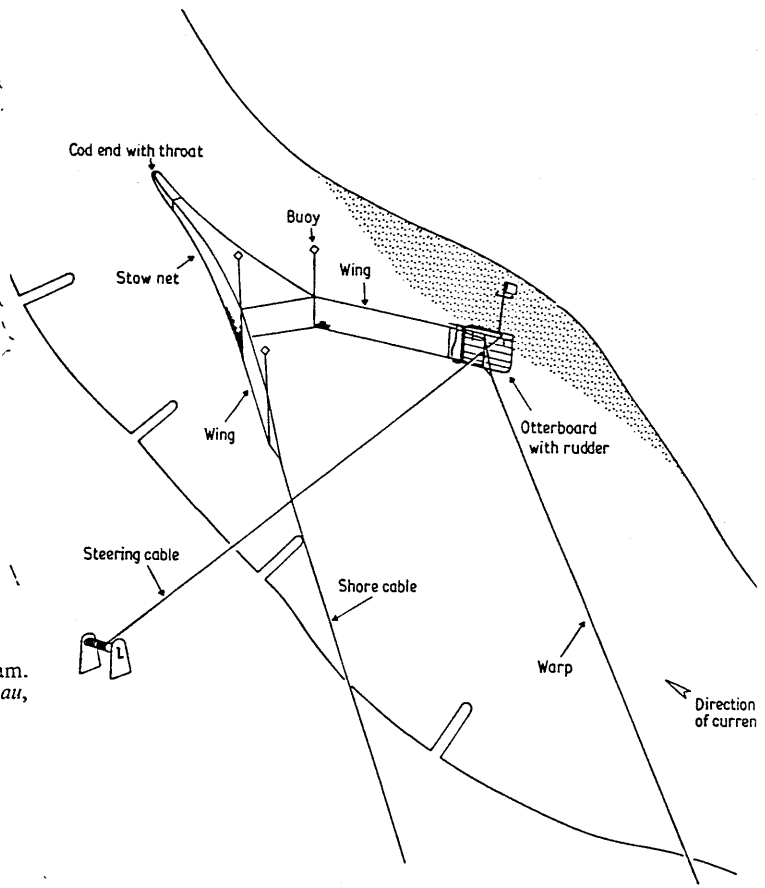


Figure 12. A variety of trap designs used for the capture of downstream migrant eels. (from Sinha and Jones 1975, Tesh 1977, Best 1977)

7. ACKNOWLEDGEMENTS

We would like to thank the many scientists and hydroelectric environmental staff who provided information and advice on fisheries matters during the recent MAF Fisheries funded overseas study tour by JAB.

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APPENDIX I
INFORMATION ON "HI-Z Turb'N tag "

F.Y.I.



Current Information on Environmental Compliance

A New Method For Turbine Passage Studies: HI-Z Turb'N Tag

Normal Procedures: For many years turbine passage survival studies have been conducted to estimate proportion of fish safely passing through hydroelectric stations. Primary methods used to assess turbine related mortality include: full or partial recovery nets, nets equipped with live cars, radio telemetry, and mass mark-recovery (coded wire tags, stains, etc.)

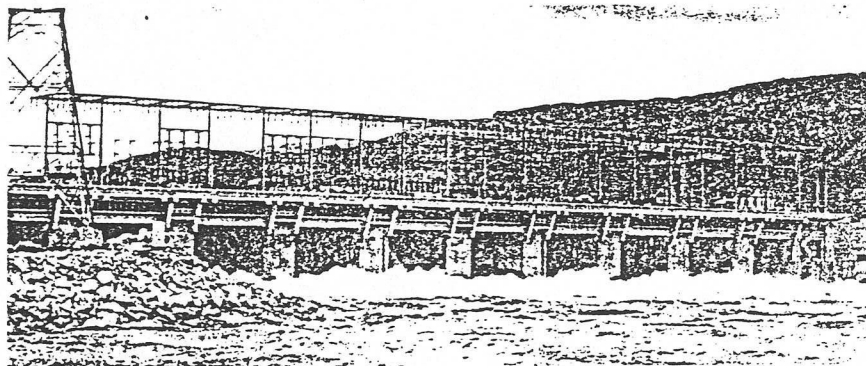
Problems: Problems associated with the normal procedures include: Nets and debris collected in the nets contribute to fish injury and mortality making it difficult to isolate turbine related mortality. Fitting nets with live cars has lessened injury and mortality but sensitive species and life stages (i.e. juvenile American shad) can still be injured. Recovery nets and live cars require special engineering and heavy equipment for installation and they can be difficult to operate in high discharge areas. These factors often make recovery nets extremely costly to construct and maintain. Tracking radio tagged specimens is labor intensive and expensive. This is especially true if the assessment of long term effects (several days) of turbine passage is required. Often, radio signals are lost after station passage. Young fish may be preyed upon, making estimates of turbine-related mortality difficult. Also, the fish is not physically recovered, and the extent of injuries cannot be determined. Mass marking fish with stains, brands, and coded wire tags require large numbers of test specimens and extensive recovery facilities or sampling programs. This technique has limited application for resident species which do not voluntarily migrate downstream. If the fish are not recovered at the power station tested but at another facility several miles down river, injury and mortality associated solely with passage through the test power station are confounded.

New Approach: RMC has been using a new method for assessing turbine-related mortality. This recently patented method (U.S. Patent No. 4,970,988) involves use of the HI-Z Turb'N Tag which is activated after turbine passage. This tag brings the fish to the surface and enables physical recovery of each turbine passed fish within minutes. After turbine passage the tag is quickly removed with minimal stress to the fish and the fish is examined for injuries and held to assess long term effects of passage. The sample size for each turbine survival study can be statistically determined prior to initiating a study thus allowing for reliable estimates of turbine passage survival. Turbine passage survival is adjusted for control mortality and confidence limits established. The HI-Z Turb'N Tag can also assess passage survival at spill structures and fish bypass facilities.

Application: The HI-Z Turb N' Tag and recovery procedure has been utilized at five hydro facilities. Fish tested include smallmouth bass, bluegill, juvenile American shad and several catfish species.

PRODUCTS & SERVICES

Fisheries Survival at Dams: Using Hydroacoustics to Forge Compromises



Officials at Wells Dam on the Columbia River reduced the percentage of fish passing through hydro-turbines by installing a diversion system based on underwater baffles. Hydroacoustic data were used to determine the most effective design for the bypass system and to estimate total project bypass efficiency after the system's installation.

Spilling Water Cost-Effectively at John Day Dam

As migrating juvenile salmon swim downriver, their bodies undergo changes that allow them to adapt to saltwater. Timely passage through dams is critical to their survival.

To pass fish quickly, dam operators may spill water through spillways or sluiceways. Doing so, however, reduces the amount of water available for electric power generation. This forces operators to perform a balancing act—maximizing power output while protecting fish.

At John Day Dam, dam operators used BioSonics' hydroacoustic technology to monitor the timing of out-migrations. In this way, they were able to "flush" fish cost-effectively, spilling water only when migrating fish reached their facility.

Developing a Successful Fish Bypass Strategy at Wells Dam

Hydro-turbines present a real danger for fish. Fish entrained into turbine intakes may be injured or killed. Others emerge so stunned that they fall easy prey to predatory birds and fish.

Wells Dam has decreased the percentage of fish passing through turbines by developing a bypass strategy that diverts fish away from turbine intakes. The design of the diversion system was based in large part on fish passage data collected by BioSonics. Studies performed after the installation of the system reveal a high bypass efficiency.

Federal Energy Regulatory Commission license conditions require the operators of Wells Dam to protect fish that migrate through the hydroelectric facility.

Soundings

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APPENDIX III

WATER VELOCITY CRITERIA FOR FISH PASS SCREEN DESIGNS

<u>AGENCY</u>	<u>NORMAL VELOCITY^a</u> (ft/s)		<u>PARALLEL VELOCITY^b</u> (ft/s)
	<u>FRY</u>	<u>FINGERLING</u>	
National Marine Fisheries Service	≤ 0.4	≤ 0.8	> Approach velocity
California Department of Fish and Game	≤ 0.33 for continuously cleaned screens; ≤ 0.0825 for intermittently cleaned screens	Same as fry	At least 2 times the approach velocity
Oregon Department of Fish and Wildlife	≤ 0.4	≤ 0.8	\geq Approach velocity
Washington Department of Fisheries	≤ 0.4	≤ 0.8	\geq Approach velocity
Alaska Department of Fish and Game	≤ 0.5	Same as fry	No criterion
Idaho Department of Fish and Game	≤ 0.5	≤ 0.5	Sufficient to avoid physical injury to fish
Montana Department of Fish, Wildlife and Parks	≤ 0.5	≤ 1.0	No criterion

- a. Normal velocity = Velocity component perpendicular to screen face
b. Parallel velocity = Velocity component parallel to the screen face, also called sweeping velocity

Performance and Findings:

Smallmouth bass (238 test, 130 control), 4 to 12 inches long were passed through a facility with vertical Francis turbines equipped with double or quad runner blades. The capacity of each unit is approximately 900 cfs. Tests were conducted at a low wicketgate setting of 60% opening. 90% of the fish that were passed through the turbines were accounted for. Short-term survival ($\leq 1h$) was 93 and 79% for the quad and double runners, respectively.

Channel catfish (177 test, 50 control) 4.7 to 12.8 inches long were passed through an S-type bulb turbine. The capacity of the unit tested was approximately 600 cfs. Tests were conducted at blade settings of 13° and 28° (near minimum and maximum). 90% of the fish were physically recovered and the status was discernible for an additional 3%. Short-term survival ($\leq 1h$) was 86 and 93% at the 13° and 28° setting, respectively.

Bluegill (105 test and 94 control) 3 to 8.7 inches long were passed through the same turbine as the channel catfish. Tests were conducted only at the low blade setting (13°). 88% of the fish were physically recovered and the status was discernible for an additional 2%. Short-term passage survival ($\leq 1h$) was 89%. Bluegill (51 test, 52 control) were also tested at another facility with Kaplan turbines (1300 CFS discharge/unit). 87% of the test fish were physically recovered. Short term survival ($\leq 1h$) on the fish (4-8 inches long) was 96%.

Catfish species (6-12 inches long) were also tested at the above facility. A total of 56 test and 51 control was released. 91% of the test fish were recovered, short term survival was 88%.

American shad juveniles (90 test, 40 control) ranging from 4-6 inches were passed through a Francis unit which discharges approximately 5,000 cfs. The status of 93% of the fish was discernible. Short-term survival ($\leq 1h$) was >80%. Juvenile American shad (299 test, 300 control) were also passed through Kaplan and mixed-flow turbines. Each unit discharges approximately 8,500 cfs. Recovery rate was 94% and short-term survival ($\leq 1h$) was >95% for all tests.

Services To You: RMC performs turbine passage survival studies directly, or licenses the HI-Z Turb N' Tag and provides training in its use.

This tag can provide an objective, reliable answer to fish passage survival and mortality at your facility.

We invite you to call us with questions regarding the tag or recovery techniques. Contact Paul G. Heisey or Dr. Dilip Mathur at (717) 548-2121.