Downstream Migration and Passage Technologies for Diadromous Fishes in the United States and New Zealand: Tales From Two Hemispheres

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ABSTRACT

In this presentation we review aspects of the downstream migration of eels and other diadromous species in the United States and New Zealand. Examples of how protective measures have been implemented in both countries are provided, and performance of structures and operational protocols are discussed.

Dam construction on the Connecticut River, USA began in the 1800s, and resulted in the reduction of distribution of most diadromous species, with some populations exterminated. Restoration of upstream passage began in the 1970s, and downstream passage provisions were first installed on lower mainstem dams in the 1980s. Initial target species for downstream passage were Atlantic salmon (*Salmo salar*) and American shad (*Alosa sapidissima*). Surface bypasses have been installed on five of the lower mainstem dams. Structure details, efficiency of the system and cost of each are discussed. Other species under consideration for downstream passage by US agencies now include: American eel (*Anguilla rostrata*), sea lamprey (*Petromyzon marinus*), and shortnose sturgeon (*Acipenser brevirostrum*).

Similarly, in New Zealand, water managers have become increasingly concerned with the downstream passage of non-salmonids and in particular eels (*Anguilla. australis and A. diefenbachii*). As turbine mortality increases with size, long fish such as eels are highly susceptible. A lack of knowledge of migration timing, migration triggers and migration pathways make development of protective measures for the less know species difficult. Furthermore, some species are so small when migrating that they can easily pass through narrow-spaced screens making even this option unsuitable, although turbine mortality for them is probably low.

Several types of protection systems for downstream migrants are available; some have been field-tested and are about to be implemented in New Zealand. These include: screens, barrier nets, lights, sound, electric fields, louvers, spills, and bypass flows. Our experience shows that a thorough knowledge of migration timing, diurnal cycles and migration pathways can lead to effective measures being implemented.

INTRODUCTION

In this presentation we review aspects of downstream migration of eels and other diadromous species in the United States and New Zealand. Although this is not a comprehensive review, either taxonomically or geographically, we hope to demonstrate that many commonalities in downstream passage problems exist among our respective habitats, and that much may be applicable to Australian species and the Murray Darling Basin.

We focus primarily on how passage problems have been historically addressed in an applied (although not always successful) manner. Examples of how protective measures have been implemented in both countries are provided, and performance of structures and operational protocols are discussed. For a more extensive review of intake protection technology please refer to EPRI (1986 & 2001).

Case study - The Connecticut River

The Connecticut River, in the Northeastern United States, is 660 km long and has a catchment area of 28,500 km^2 (**Figure 1**). Damming, which began in the 1800s, had a major effect on the distribution of diadromous fishes and extirpated several species. Restoration and provision for upstream passage did not begin in earnest until the late 1970s. Restoration of upstream passage led to the development and construction of downstream passage structures during the 1980s (Moffitt *et al.* 1983).

Initial target species for downstream passage were Atlantic salmon (*Salmo salar*), primarily in the smolt stage, and juveniles of the American shad (*Alosa sapidissima*), an anadromous clupeid. Juveniles of both species are relatively small, (130-250 mm FL for salmon and 70-120 mm FL for shad), and form schools that are primarily surface-oriented. Timing of the migrations of the two species is different, with salmon smolts moving downstream in spring (April to May) while shad juveniles migrate downstream in autumn (September to October).

Although passage provisions were implemented primarily for juveniles it is important to note that adults of both species commonly migrate downstream after spawning, and also present different passage problems due to their larger size (500-900 mm FL for salmon and 350-500 mm FL for shad) and different timing of migration (late autumn/winter for adult salmon and late spring for shad).

On the mainstem of the Connecticut River there are five major dams where extensive downstream passage facilities have been constructed: Wilder, Bellows Falls, Vernon, Turners Falls, and Holyoke Dams (**Figure 1**). Downstream passage technologies installed at these dams were considered, at the time of implementation, state-of-the-art designs that had been developed for juvenile salmonids, primarily in the Western USA and Canada. Facilities installed at the lowermost four dams are summarised in **Table 1** and described in more detail below.

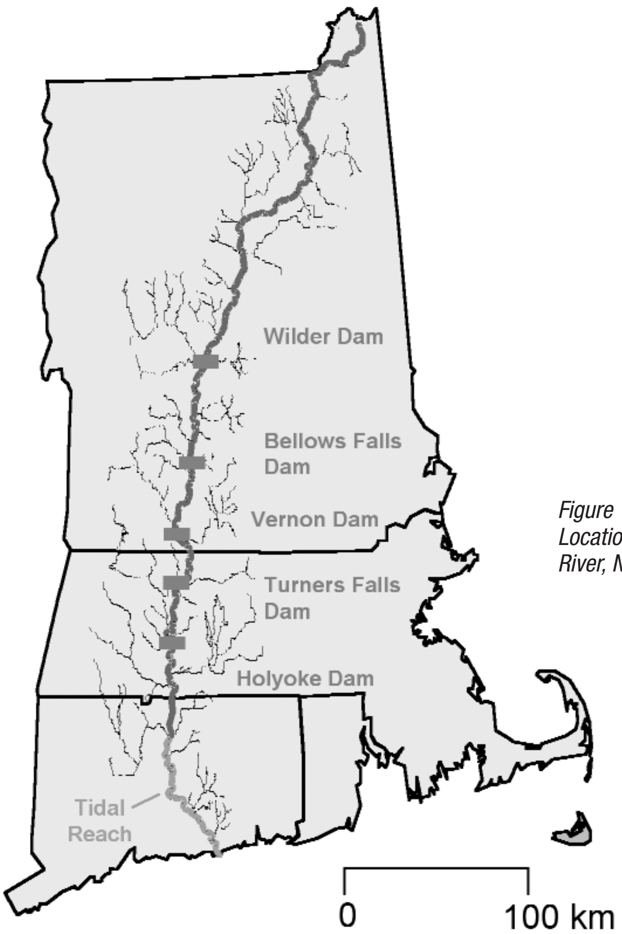

Figure 1.
Location of the five lowermost dams on the Connecticut River, Northeastern USA.

Bellows Falls Dam

Bellows Falls Dam, at river kilometre 280, is the furthest dam upstream from the ocean with a major downstream bypass facility (although other dams further upstream have some minor downstream passage facilities, i.e. mandated sluice spill without guidance structures). At this site, up to 283 m^3/s of river flow is passed through an excavated power canal to the powerhouse and about 7.1 m^3/s (c. 2.5% of the maximum station flow) is diverted to a downstream bypass sluice positioned at the end of a concrete diversion wall (**Figure 2**).

The concrete diversion wall extends across the c. 12 m deep forebay to a depth of 3.5 m. Fish are diverted into an existing 4.5 m wide trash sluice (without trash screen) equipped with a modified concrete channel exit, where they free-fall into the tailrace. Total cost of this facility was about US$3.5 M. Bypass efficiency for smolts through this facility, as estimated by radio telemetry, is about 80%, but has not been evaluated for other species.

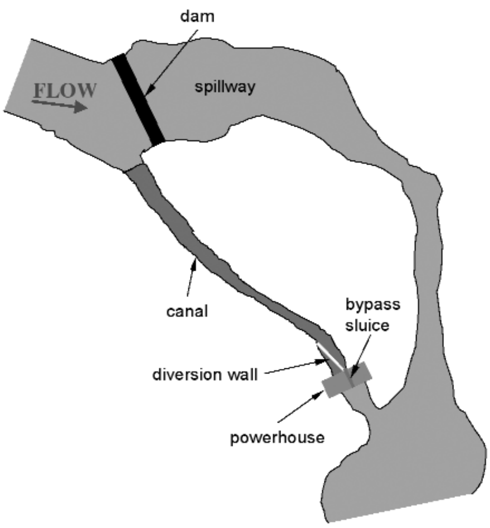

Figure 2. Site plan, Bellows Falls Dam, Connecticut River, Vermont, USA.

Vernon Dam

The next dam downstream is Vernon Dam, at river kilometre 229. This facility passes a maximum of 269 m^3/s through the powerhouse and about 10 m^3/s (c. 3.7% of maximum station flow) is by-passed through an existing rectangular pipe to the tailrace (**Figure 3**). This type of bypass is fairly typical of most northeastern dams without a power canal where provision is made for downstream migrants by simply diverting flow through an existing opening, (usually a debris or ice sluice).

There is a 3 m high surface concrete wall in the open forebay of the Vernon Dam to guide fish towards the bypass. Although this guide wall is downstream of a floating log boom, large amounts of debris still accumulate at the relatively narrow bypass entrance, and this has necessitated the installation of a trash rack with 300 mm spacing at the bypass entrance. The total cost of the Vernon facilities was about US$2 M. Bypass efficiency for smolts at this site is estimated at approximately 80%.

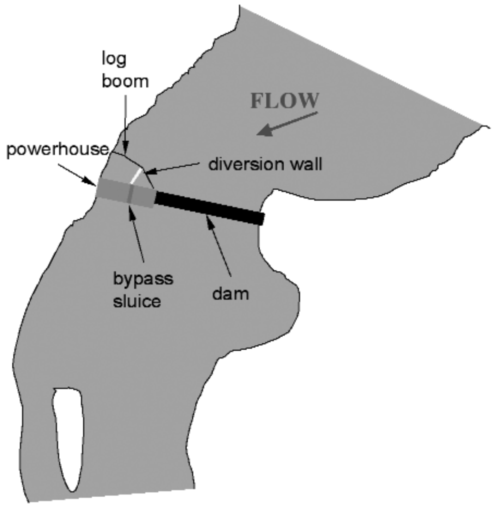

Figure 3. Site plan, Vernon Dam, Connecticut River, Vermont, USA.

Turners Falls Dam

Turners Falls Dam, at river kilometre 198, diverts a maximum of 354 m^3/s of water through a 4.5 km long canal to a powerhouse; c. 8 m^3/s of this flow (about 2% of maximum station flow) is diverted to a surface trash sluice (**Figure 4**). Because of the relatively high water velocities in the canal and forebay, diversion walls as installed at the upstream dams were considered too technically difficult to construct at this site. As an alternative, bar spacing in the upper four metres of the 10 m deep trash rack was reduced from 100 mm to 25 mm with plastic inserts in an effort to reduce entrainment of surface migrants. The bypass entrance itself was also modified with a bell-shaped insert, which causes water to accelerate gradually and smoothes the transition of flow from the forebay to the trash sluice (Haro *et al*. 1998). Bypass flow from the sluice is diverted to the tailrace directly, without a free fall. The cost of these modifications was about US$1.5 M. Efficiency of the bypass is about 80% for salmon smolts, but less than 3% for catadromous eels.

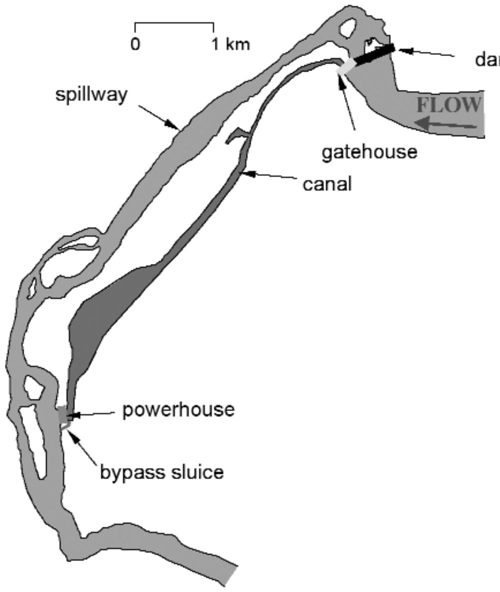

Figure 4. Site plan, Turners Falls Dam, Connecticut River, Massachusetts, USA.

Holyoke Dam

The lowermost extant dam on the Connecticut River, Holyoke Dam supplies one in-line powerhouse and several smaller stations and mills via an extensive series of canals. The in-line hydro station has a capacity of 238 m^3/s. Downstream migrant fish are diverted either to the spillway through a modified surface bascule gate or are diverted out of the canal by a louver array and bypass pipe.

The upper three metres of the intakes to the main powerhouse at Holyoke Dam are covered with a solid overlay to guide migrants to the bascule gate and trash sluice; the bascule gate entrance has been modified with uniform acceleration weir. Migrants entering the canal (170 m^3/s max. flow) are guided by the louver array, which has steel vanes with 100 mm spacing extending down to the full 7 m depth of the canal. At the downstream end of the array, migrants are guided into a 1 m diameter steel pipe, which opens into the tailrace via a concrete channel. Total costs were US$50 K for the bascule gate modifications and US$10 M for the louver array and bypass pipe. Bypass efficiency is estimated at c. 80% for smolts but is unknown for other species. However, as both guidance structures are susceptible to fouling by trash, efficiency is probably often lower. Performance of the protection system is also expected to depend on forebay levels and canal flow.

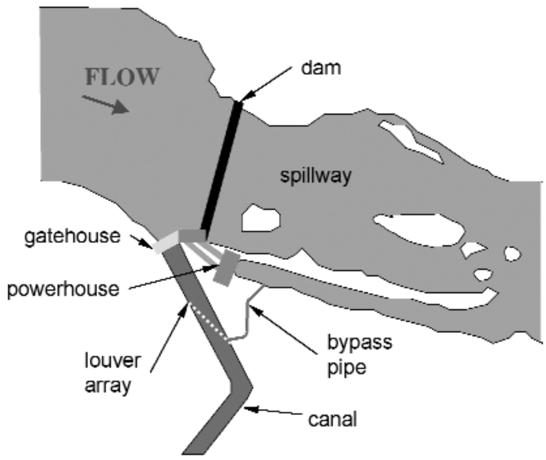

Figure 5. Site plan, Turners Falls Dam, Connecticut River, Massachusetts, USA.

Downstream passage for other species

Several other fishes are now being considered by US resource agencies as target species for downstream passage. These include:

- American eel (*Anguilla rostrata*), a catadromous species that migrates downstream as adults (500-1000 mm TL) and is experiencing declines in their populations throughout their range.
- Shortnose sturgeon (*Acipenser brevirostrum*), which undergoes extensive upstream and downstream migrations as juveniles and adults (250-1700 mm TL) during their long lifetimes, and listed as endangered by State and Federal agencies.
- Sea lamprey (*Petromyzon marinus*) an anadromous species considered less important as a resource, but with very little known about their migrations and potential impacts of hydroelectric operation, particularly on emigration and survival of juveniles (200-230 mm TL).

It is likely that other species of diadromous and potamodromous (or wholly riverine) fishes will be added to this list in the future.

Turbine mortality

When passing through turbines fish are subjected to pressure changes, cavitation, shear stresses, and mechanical strike (Coutant & Whitney 2000). The effect of pressure change, according to these authors, is most severe on larval fish but in our view this effect needs more study. Hydraulic shear and cavitation affects primarily medium size fish, while mechanical strike is most likely with longer or larger fish. Because of the wide type and size of power plants installed, and also because of the flexible way each one can be operated, measured mortality rates have been highly variable. For example, measured mortality rates of eels along the East Coast of North America have varied between 20-100% for Kaplan turbines and 6-76% for Francis. In general, small and higher speed turbines do the most damage, and an indication of the loss expected can be derived from the formula provided by Larinier & Travade (2002) that relates mortality rate to fish length, and turbine characteristics.

Intake protection devices

Mechanical barriers

Screens

Intake screens are, without doubt, the most effective and reliable means of protecting intakes, and criteria for their design and operation are available in many US states (e.g. look for FERC/WD in the Hydro Program page of the NOAA website **http://www.nwr.noaa.gov**). Traditionally, intake screens have tended to be rotating drums but these are expensive to install and operate. More recently, both in the US and New Zealand, angled flat screens have become more popular, with multiple labyrinths installed where large flows are involved (e.g. a screen facility has been proposed for a site on the Waitaki River in the South Island of New Zealand where 340 m^3/s are to be diverted by seven labyrinth-style screens each 35 m long and 5 m deep, angled at 9o to the flow, and with 5mm bar spacing. At the end of each set of screens or labyrinths a bypass channel returns deflected fish back to the river, but where there are other power plants downstream, some means of safely transferring the fish past the last barrier should be considered. In most instances this means road transport or barging.

Cost of screening is highly variable and depends on the size of the installation and local conditions, but typically small intakes (0.2-1.5 m^3/s) are expected to be in the order of US$ 100-200 K per m^3/s. Larger intakes can be relatively more expensive to install; for example the cost of screening at the Rocky Reach Dam, Columbia (170 m^3/s) was approximately US$85 M, while for the McKenzie River Dam (70 m^3/s) the cost was about US$12 M.

What has been shown to be effective for one species and life stage may not, however, necessarily work for another, and we recommend careful investigations before systems are implemented. Eels, for example, are adept at negotiating small spaces, and easily pass through narrow-spaced screens that have been shown to be effective for large salmonids. High water velocities exacerbate both impingement and entrainment with bar spacing as small as 20 mm, allowing smaller migrant eels to pass through, but impinging and suffocating any retained by the screens. Some efforts have been made to minimise this problem by reducing both through-screen velocities and screen spacing. For example at La Pulpe Power Station on the Rimouski River in Quebec, vertically inclined screens with a spacing of 10 mm were successfully tested and implemented (Therrien, in press). Although such screens effectively excluded most migrants, they are often plagued by other problems such as clogging with debris and formation of frazil ice. Installation of a compressed air cleaning system alleviated some of these problems, but the design remains impractical for large intakes.

Barrier nets

Barrier nets can be an effective means of excluding fish, and are cheap to install (e.g. NZ$10-15 K to exclude migrant eels from a 54.7 m^3/s average flow intake). Maintenance and running cost are, however, very high and in effect the system can only be used where there is little, if any, drift material present. This system has been installed in combination with a trap and transfer operation to protect downstream migrant eels in New Zealand, where the net is only deployed in autumn when more than 40 mm of rain has fallen in the catchment, and only when the amount of aquatic plant drift is low (Boubée *et al*. 2001).

Behavioural barriers

Behavioural barriers use the avoidance response of fish to external stimuli as a means of protecting intakes. The most common of these are lights, electric fields, sound and a combination of these, often in combination with bubble curtains.

Lights

Because some fish species migrate primarily at night and are photonegative (i.e. they avoid lights at night), arrays of surface and underwater lights (and in particular strobe lights) have been promoted as an a means of excluding eels and other fish from intakes (e.g., Hadderingh *et al*. 1992). However, this method has an appreciable effect only when water velocities are very low and water clarity is exceptional, and even under these conditions guidance is not 100% effective. In turbid water (and because eels migrate downstream mainly during floods water is invariably turbid), the intensity of light declines rapidly and the system becomes ineffective. Furthermore, some fish species are attracted to light, and this is often used as a means of attracting some downstream migrants, notably salmonids, to bypasses. Therefore, installation of light barriers can compound the problem of entrainment, and in our experience can also increase predation. As with all behavioural systems, fish tend to habituate to artificial illumination, and light barriers can become ineffectual if fish remain in the illuminated area for some time. Although the cost of installation is, in comparison to screens, relatively cheap (e.g. NZ$25 K for material in a trial for one of the four 9 m^3/s intakes at the Huntly Power station, Waikato R. New Zealand), the cost of maintaining the lights free of algae, keeping cables and lines free of debris, and ensuring the system remains water tight can make the system impractical.

Sound

Fish react to sound, and there are various systems on the market, including some that combine light, air bubbles and sound (e.g. Fish Guidance Systems Ltd). Some investigators have experimented with intense, low frequency sound, as low as 10 Hertz, to repel eels from intakes (e.g. Sand *et al*. 1999). Although eels display a negative response to such sounds, the response occurs when fish are within only a few meters of the sound source, again limiting the effectiveness of sound as a deterrent at large-scale sites. Generally, the system appears to be effective in lakes and estuaries but has often failed in high velocity zones, noisy sites, or in deep waters.

Electric fields

Electric fields have been shown to be useful on small schemes for upstream migrants and have been used successfully to protect small intakes. There is, as yet, no conclusive evidence that they work for downstream migrants.

Louvers

In some ways louver systems can be considered a behavioural system as they largely rely on the visual avoidance response of fish to a barrier. Guidance efficiencies of up to 90% have been reported with salmonid fry, but the system has not been fully tested with other species. Large spacing between the vanes is a possibility if a lower protection level is acceptable (e.g. 60% exclusion for 250 mm spacing).

Diversions

Spills

Other approaches to protection of downstream migrants have advocated employing controlled spill as a methodology, especially for those species (like eels) that emigrate during high flow events. The methodology requires no outlay of capital but cost can be high due to loss of water that could potentially be used for generation. Simulations of "programmed" spill events for passage of eels dependent on river flow has shown the potential for reducing turbine mortality by as much as 50%, with minimal loss of generation (Haro *et al*., in press).

While it is logical to assume that migrants passed via spill will not be subjected to risks of turbine passage, the risks of injury, disorientation, or subsequent predation due to spill passage may in some situations be equally as great. This is an area that deserves additional investigation, for fishes of both large and small sizes.

Trials at Patea Power Station in New Zealand which has an 80 m high dam indicated that opening one of the three spillway gates by about 70 mm resulted in very little damage to migrant eels (Boubée & Watene 2001) and was effective for eels if well timed and intake shut off or reduced.

Bypass flows

Although bypass flows of about 2-5% of the total flows are often advocated (e.g. Odeh & Orvis 1998), smaller flows can be just as effective for some species. The critical factor in determining the efficiency of a bypass is its position, and judicious placement of deflecting wall and screens has often increased efficiency considerably. Locating the most effective position for a bypass is best done by means of acoustic or radio telemetry, but as our understanding of the behaviour of individual species improves it is expected that modelling will be able to define potential aggregation points.

At Wairere Falls Power Station in the North Island of New Zealand, simply providing two adjacent 100 mm diameter apertures between the two main intake screens (cost of about NZ$5 K) has permitted the safe passage of close to 10% of tagged migrant eels released in the head race. It is expected that the addition of other better-positioned and slightly larger bypasses, preferably combined with effective protection measures at the intake, will virtually eliminate existing migrant eel impingement and entrainment problems at this site.

Location and design of intakes

When constructing new intakes it may be possible to position the structure in areas that are relatively free of migrant fish. Operating the intake at times when there are few fish migrating is another possibility. Such measures are particularly important when the species or life stage of concern cannot be effectively screened out. For example in the lower Waikato River in the North Island of New Zealand, upstream migrating juveniles were found to use low velocity zones along the littoral and river bed, rather than the main river channel. Locating the intakes (cigar shaped cylinders covered in 1 mm slot wedge wire) away from these migration zones ensured these small migrants remained protected. Also, large numbers of larval fish migrate downstream in the Waikato in autumn and mainly at night. Studies have indicated that greatest densities of larvae occur at the surface and along the river bottom. Since larvae cannot be effectively screened out, positioning the intake in mid water in the middle of a deep channel would minimise entrainment. Further reduction in entrainment could also be achieved by minimising abstraction at the peak of the migration which occurs in autumn and at night.

Conclusions

Although there are a multitude of intake protection devices available, most downstream passage devices to date have been designed primarily for juvenile salmonids, or adapted from salmonid designs. Protection for other species or life stages may require development of entirely new or more radical technologies. Our experience shows that to design an effective intake protection system, a thorough knowledge of the species of interest is essential. Information needed includes:

- Migration patterns (seasonal and diurnal activity),
- Migration triggers,
- Depth of migration,
- Migration pathways,
- Behavioural response to the barrier (e.g. searching behaviour),
- Behavioural response to the potential protection device (e.g. to light, sound, screens, flow etc.)

Monitoring facilities and a monitoring plan must be part of the protection measures implemented, not only to determine the effectiveness of the protective measure but also to obtain an indication of the success of modifications that invariably need to be made. A maintenance plan must also be devised. Finally, but not least, a thorough literature review and expert advice should be sought so as not to repeat mistakes made elsewhere.

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Table 1. Downstream fish protection measures installed on the four lowermost hydro dams of the Connecticut River, USA.

Location	Type of plant	Inland distance (km)	Plant capacity (m^3/s)	Guidance system	Bypass volume (m^3/s)	Efficiency (%)	Cost ($US)
Bellows Falls Dam	Canal	280	283	3.5m high concrete wall at surface of 12m deep canal	7.1	Smolts 80	3.5M
Vernon Dam	In line	229	269	3 m high concrete wall at surface of forebay	10	Smolts 80	2M
Turners Falls Dam	Canal	198	354	Bar spacing reduced from 100 to 25mm in upper 4m of 10m high screens	8	Smolts 80 Eels <3	1.5M
Holyoke dam	In line & canal	138	238 & 170	Solid overlay in upper 3m of screen & Louver, 100mm spacing full 7m depth	18 & 4	Smolts 80	50k & 10M