Blocking or guiding upstream-migrating fish: a commentary on the success of the graduated field electric fish barrier

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Abstract

Fisheries managers have been interested in the control of fish movement for a variety of reasons and for a considerable period of time. The most common reasons are the containment of invasive species and the protection of all or selected fish species at industrial installations such as hydroelectric stations and the cooling water systems of thermal power stations. The use of electricity has proven to be most popular in the prevention of upstream passage at hydropower tailrace sites and also at river and canal sites selected as the last line of defence against the spread of invasive species. At other locations electric barriers are deployed to block and guide upstream migrants towards census facilities. In the past the reliability and operational safety of electric fish barriers has been an issue but these concerns have been overcome by advances in fisheries technology associated with the demands of large installations. A significant number of graduated field electric fish barriers have been installed in the USA and other parts of Europe where electrode arrays are deployed on or in the river bed. They present upstream migrants with higher voltage gradients as fish progress into the field, eventually causing their downstream drift to safety. This paper reviews the performance of several electric fish barriers in the USA and Europe. Monitoring has shown that the graduated field fish barrier is effective in preventing upstream migration past the barrier location.

Keywords: graduated field electric fish barrier, control of fish movement using electricity, non-lethal fish guidance, fish deterrence technology.
1 Introduction

For many varied and complex reasons, fisheries managers have been interested in controlling the movements of fish over several decades. Historically, the deployment of electric fields for this purpose has had mixed success and in recent years the use of electricity to influence the downstream movement of fish has been all but abandoned with the exception of locations with water velocities at or below 0.3 ms\(^{-1}\). However, the control of the upstream movement of fish using electricity continues to receive the support of regulatory authorities in many parts of the world. Concerns about reliability and human and animal safety have largely been allayed and the modern technology now used in the design, construction, installation and management of electric fish barriers has increased confidence in the use of electric fish barriers.

The literature contains a wealth of information on past studies which have led to the successful outcomes of today. McGrath et al. [1] describes how, in 1931, a temporary electrified fish screen was erected across the tailrace of Ardnacrusha Power Station on the River Shannon in Ireland, at the point of return of the tailrace to the natural river channel, to prevent the entry of adult salmon. The maximum depth of water at this point varied from about 4.5 m in summer to about 7.6 m in winter. A series of 6 mm galvanised iron chain electrodes were suspended from two catenaries slung across the waterway to make a barrier about 52 m wide. The electrodes were energized by 133 V AC, a special 10,000:133 V transformer being wound for the purpose. The two electrode arrays were placed about 3 m apart and the individual electrodes in the same array were spaced 0.6 m from each other. Due to a number of factors, including the difficulty of maintaining the barrier while at the same time preserving navigation facilities in the channel, the barrier was not maintained for any length of time and it was dismantled.

Relatively large scale electric fish screens (greater than 50 m wide) were also deployed at a number of hydroelectric tailraces in Scotland during the 1950s (e.g. Shin tailrace). For a variety of reasons most of the larger electric fish screens were eventually replaced by conventional physical screens with bar spacing in accordance with legislative requirements.

During the 1950s and 1960s AC and later DC single electrode arrays were deployed at up to 100 locations in Great Lake tributaries as part of the sea lamprey control program. However, these rudimentary electric barriers were soon discontinued owing to interference with the upstream movement of non-target fish species and were substituted with chemical control methods and/or low head physical barriers.

The above examples show that electric fish barriers have been around for some time and Vibert [2] provide a useful summary up to the mid-1960s. In [2], Hartley and Simpson [3] also summarized electric fish screens in the UK until the mid-1960s. The next information consolidating publication appeared in 1990 when Cowx and Lamarque [4] edited the proceedings of a symposium on fishing with electricity. In [4], Stewart [5] provided a review of electric fish screen installations in many parts of the world. Reliability of operation remained
a concern to regulators and fisheries managers who were interested in deploying
the technology in the interests of fisheries conservation. There is also a first
mention of a graduated field electric barrier in [5] but this reference was to some
experimental work being attempted in Europe at laboratory level. While Smith-
Root Inc. was listed as a sponsor of the symposium whose proceedings formed
the content of [4] there is no mention of the Smith-Root Inc. graduated field fish
barrier (GFFB) which had been designed during the mid-1980s and installed for
the first time at a location in Oregon, USA, during 1987. A report for the UK
Department of Trade Industry (Turnpenny et al. [6]) contains a generalised
description of the Smith-Root Inc. GFFB in the context of UK intake fish-
screening regulations with particular reference to hydroelectric power schemes.
Hilgert et al. [7] provides one of the first published evaluations of the
performance of a GFFB and stated that this technology represented a substantial
improvement over AC fish barriers and a sophisticated refinement over single
field DC barriers. Clarkson [8] provides a comprehensive description of the
GFFB installation and operation for systems installed and monitored as part of
the Central Arizona Project during the years 1988–2000. Most of the
recommendations made in [8] which relate to GFFB standard operating protocols
and remote monitoring have been implemented by Smith-Root Inc. during the
intervening years.

This paper provides a generalised description of the GFFB and also presents
information on GFFB installations at locations throughout the USA. This
information is largely based on peer reviewed publications.

2 Description of the graduated field fish barrier (GFFB)

The Smith-Root Inc. website [9] contains a comprehensive description of the
requirements for the installation and operation of a GFFB (Fig. 1) together with
information on installations at various locations through the USA. The essential
components of a GFFB are the electrode array, the programmable output
waveform pulsators (POWs) which energise the electrode array and the hardware
/software fish barrier telemetry and control system (FBTCS) used to manage the
operation of the POWs and communicate remotely with personnel responsible
for the day to day performance of the GFFB. At an early stage in the GFFB
installation process, civil engineering drawings are prepared which are based on
site specific information (channel width, channel depth, substrate composition,
water conductivity, water velocity – ideally uniform and a minimum of 0.6–
0.9 m sec\(^{-1}\)) and expected variations in these parameters. Depending on the
objective of the installation e.g. temporary or permanent facility, the electrode
array may be mounted on plastic insulated mats or insulated concrete. At some
large installations railroad rails have been used as electrodes while at smaller
sites 2.5cm diameter stainless steel tubes have been deployed.

Standard POWs are rated at 1.5kw and depending on the width, depth and
water conductivity multiples of these standard POWs may be deployed or
customised POWs may be selected which have a much higher rating to match
expected power demand. The dimensions (depth/width/length of electrode
The operation of all POWs is controlled by a master POW (the others are termed slaves). The slave POWs operate at the master POW settings so that the electric fields generated in the water are additive and cumulative. The nature of the graduated field is complex and depending on the location of voltage gradient measurement (at the surface, adjacent to electrodes etc) readings may vary. For operational purposes, target voltage gradients are measured at the surface. Approaching the downstream electrode (always negative) from downstream of the electrode array, there is an increase in voltage gradient. This increase continues up through the barrier and reaches its maximum approximately midway through the electrode array which is normally about 6m long and can accommodate a total of seven electrodes with 1m spacing and powered by six POWs. The location in the electrode array where the maximum voltage gradient occurs can be altered by adjusting the maximum output voltage of one or more POWs. The shape of the graduated field and the location of the peak voltage gradient can be varied by increasing the voltage applied between selected electrodes and by varying the spacing between selected electrodes.
electrodes. The deployment of equally spaced electrodes with equal voltage applied between them produces a uniform field with a graduated voltage gradient entry. In general, field and laboratory measurements of voltage gradients show that at the surface, voltage gradients are more uniform while at the substrate and adjacent to electrodes they are more variable.

Savino et al. [10] provides a three-dimensional diagram of voltage gradient readings at a temporary GFFB in the Shiawassee River, Michigan which was installed at a low water velocity site (0.03–0.05 m s\(^{-1}\)) to test its deterrence effect on the downstream movement of round goby (*Neogobius melanostomus*). The GFFB was almost 100% effective and Fig. 6 in [10] shows that the voltage gradient was highest at the centre of the electrode array and measured 4.9 v cm\(^{-1}\). GFFBs are normally powered by mains electricity and it is also standard practice to have a back-up generator rated appropriately for the site and also matching switchgear which will allow the generator to operate immediately in the event of mains electricity failure.

The FBTCS allows for the remote control and automatic adjustment of POW settings in line with different power demand from the GFFB associated with changing water levels and water conductivities etc. In the unlikely event of GFFB failure the FBTCS automatically alerts designated personnel by email or text message so that the duration of any outage or malfunction of the GFFB can be minimised.

### 3 Deployment of the graduated field fish barrier

#### 3.1 Invasive species control

This section of the paper reviews selected published work on the control of the upstream movement of invasive species through the deployment of graduated field fish barriers.

#### 3.1.1 Sea lamprey (*Petromyzon marinus*)

Swink [11] carried out mark–recapture studies which indicated that a pulsed-DC electrical barrier set to a 2 ms pulse width and 10 pulses s\(^{-1}\) completely blocked the spawning migration of sea lamprey in the Jordan River, Michigan. Untagged sea lamprey and those from the downstream releases were often observed swimming or attached to rocks on the stream bottom within 1.0 m of the most downstream electrode. It was concluded that the pulsed-DC electrical barrier should help reduce the use of chemical lampricides for controlling sea lamprey in some Great Lakes streams and would be particularly suited for streams where even the smallest low-head barrier would create an unacceptably large impoundment. However, there is no mention of the voltage gradient required to prevent the upstream movement of sea lamprey at GFFBs in [10].
3.1.2 Bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*)

The containment of silver and bighead Asian carp in the Chicago Sanitary and Shipping Canal (CSSC) and the prevention of their escapement into the Great Lakes from the Mississippi Basin is probably the greatest challenge presented to GFFB technology anywhere in the world. Moy et al. [12] have reported on the design of the initial CSSC 350kw dispersal barrier demonstration project which was completed in April 2002. The selected site was 49m wide by 7.6m deep and the electrode array was 16.5m long with each electrode made from 3.8cm diameter steel cable in bundles of six. The design specifications of Barrier II were based on the performance assessment of the demonstration barrier [12]. Barrier II is in fact a permanent installation comprising two barriers, Barrier IIA (operational since April 2009) and Barrier IIB (operational since October 2010). The combined power output from these barriers is 3500kW with Barrier IIB serving as a backup unit whenever Barrier IIA undergoes maintenance. These barriers are 67m apart, each electrode array is 40m long and the total number of solid steel billet electrodes is 84. The task of the dispersal barriers in the CSSC is high profile, political and the economic and biological consequences of failure are enormous. The operation of the barrier system has been reported on by the US Army Corps of Engineers who have summarised several commissioned studies. Ongoing research is being carried out to determine and refine the optimum operating parameters for the barriers to ensure they are effective at containing Asian carp and all information available to the Corps indicates that the barrier system is working as designed. There is ongoing intensive electro-fishing and netting both above and below the electric barriers to monitor these areas for Asian carp presence. Results show that the barriers are effective against all sizes of fish currently believed to be in the vicinity of the fish barrier system. All prior and current field research near the barrier system indicates that the fish barrier system is effective. This research includes telemetry tests conducted by the Corps since 2003 indicating that adult-sized fish do not cross the barriers. Telemetry tests on 81 tagged fish in the CSSC since 2010 have detected 64 of those fish over 620,000 times, but none of the tagged fish has crossed any of the barriers [13]. The emerging technology of environmental DNA (eDNA) surveillance has also been used to search for the presence of Asian carp DNA upstream of the barriers. Of 114 samples taken at each of two sampling areas (228 samples), none showed evidence of bighead carp presence while a single sample showed evidence of silver carp presence – indicating the effectiveness of the GFFBs [14]. While there are purported detections of Asian carp eDNA from Great Lakes water samples (e.g. Jerde et al. [15], there have been only two actual fish sightings and these could be a result of unauthorized fish transplants or overflow floods from the Des Plaines River (a tributary system known to be inhabited by Asian carp) rather than any failure of the electric barrier.

There are concerns that small young-of-year carp might be able to pass the barriers unless barrier settings are altered to prevent the passage of these small fish. However, to date it is believed that these small fish are approximately 40km downstream of the barriers and of no immediate threat to the efficacy of the
barriers. The GFFB system on the CSSC is part of a multi-tiered Asian carp strategy that includes physical blockades, aggressive monitoring, the development of long-term biological controls and the strong collaboration of Federal agencies and Great Lakes states.

3.2 Escapement prevention and estimation

Palmisano and Burger [16] refer to the use of electric barriers to guide, direct and control fish migrations in literature from the USA dating from the 1950s through the 1970s. At many GFFB sites in the USA the objective is to block the upstream migration of adult salmonids and to guide them into broodfish collection facilities or census traps. In [16], the effective use of a portable electric barrier in association with an upstream trap was demonstrated in the estimation of Chinook salmon (Oncorhynchus tshawytsha) escapement in the River Killey, a turbid Alaskan stream.

On the River Bush, Northern Ireland, an electric barrier is deployed to prevent adult Atlantic salmon (Salmo salar) passing over a weir. Instead, these fish are guided to an upstream trap which is an important index in Europe-wide attempts to monitor marine survival of Atlantic salmon. On this river, the barrier energiser units were recently replaced, having performed satisfactorily on a 24/7 basis for the past 35 years.

Farmed adult salmon escape from sea cage culture sites along the coasts of many European countries and fisheries management agencies are often tasked with the prevention of their entry to neighbouring rivers to eliminate the possibility of inter-breeding between wild and farmed fish. The installation of a GFFB on a river susceptible to such events offers the authorities the possibility of not operating the GFFB in normal circumstances but then switching on the system in the event of an escape from a nearby salmon farm. Recovery of large numbers of escaped fish could easily justify the economic investment in the GFFB system.

3.3 Excluding fish from tailrace environments

There is growing interest on the part of owners and managers of hydroelectric generating stations fuelled by rivers which support valuable migratory fish species in the installation of GFFBs at the confluence of the tailrace and the natural river. Two such installations have already been completed in Europe, one on the River Trent at Beeston Hydro and the other on the River Arve at Vessy, Switzerland. At Vessy hydroelectric station (Anon [17]) it was found that all radio tagged trout (Salmo trutta) released downstream of the confluence of the Vessy hydroelectric station tailrace and the River Arve were excluded from the tailrace by the GFFB and migrated upstream via the natural river and associated fishways.
3.4 Aquatic macrophyte control

Maceina et al. [18] confined triploid grass carp (Ctenopharyngodon idella) to a 350 ha embayment of Lake Seminole, Georgia, where these fish were stocked for aquatic vegetation control purposes. The containment was successful despite having to turn the GFFB off (off-on operation of the GFFB triggered by motion detection system) to facilitate boat traffic. This is a good example of a still water GFFB deployment.

Verrill and Berry [19] deployed an electric barrier downstream of North and South Heron Lakes, Minnesota with the objective of preventing the ascent of common carp (Cyprinus carpio) and bigmouth buffalo (Ictiobus cyprinellus) to the lake. Their objective was to enhance aquatic macrophyte production for waterfowl. A combination of electric barrier operation and lake drawdown proved successful. These authors found that of 1,600 fish tagged in an effort to determine the effectiveness of the electric barrier, no tagged fish were among the 3,376 fish caught upstream of the barrier.

4 Discussion

There is a view [8] that any fish barrier which is not 100% effective is, in fact, ineffective. There is also the view that any fish barrier can be made 100% effective, provided the GFFB design and associated standard operating protocols are effective against component failure, lightning strikes and human error. Attaining the 100% efficiency mark is also a reflection on how much commitment funding agencies are prepared to make in the fight against the dispersal of invasive species which is a problem making overwhelming demands on public purses wherever biodiversity and ecological status are threatened.

At many locations throughout the USA, GFFBs have been deployed as barriers to the upstream movement of invasive fish species (e.g. sea lamprey, Asian carp species) and have proved to be an invaluable tool in preventing the dispersal of these invasive species. The ultimate goal in these situations is to block the passage of fish at any cost to the invasive species, even if this means the eventual death of invasive fish through repeated attempts at passage past the barrier.

Where GFFBs are deployed to block the upstream passage of native salmonids etc and perhaps facilitate broodfish collection at an adjacent trap, it is desirable that upstream migrants are presented with an alternative and suitable passage route. Otherwise, salmonids on their upstream spawning migration may make repeated attempts to swim past the barrier to the detriment of their survival and perhaps the quality of their gonadal product.

In many European countries the legal requirement to prevent the upstream movement of migratory salmonids (mainly Atlantic salmon and sea trout) into hydroelectric tailrace environments presents further opportunities for the deployment of GFFBs. To date, two such European installations have been completed at Beeston Hydro, River Trent, UK and Vessy Hydro, River Arve,
Switzerland. Both installations have performed satisfactorily since they were installed in 1999 and 2005, respectively.

It is also clear that the GFFB has the potential to act as a filter for the prevention of the upstream movement of selected fish species. The range of voltage gradient thresholds for freshwater fishes is 0.05–5.5v cm⁻¹ [8]. For example, the voltage gradient required to prevent the upstream movement of sea lamprey is 1.8v cm⁻¹ while that required to prevent the ascent of steelhead (*Oncorhynchus mykiss*) is about 0.9v cm⁻¹. An intermediate setting will therefore allow the passage of sea lamprey (a listed and protected species throughout Europe) while blocking the passage of adult steelhead for e.g. broodfish collection purposes. The depredations of marine mammals on migratory salmonids on the lower reaches of European rivers are well known and these animals can be deterred at GFFB settings which produce a voltage gradient of 0.6v cm⁻¹.

Physical screens deployed at the confluences of tailraces and natural rivers will also act as filters in accordance with the bar shape and bar spacing. In Britain and Ireland, tailrace bar screens have typical bar spacing of 4 or 5cm, the legal specification at which adult salmon migrating upstream are deemed protected. Small one-sea-winter Atlantic salmon can squeeze through 5cm bar screens and there is a high profile example of this situation in Scotland (A. Stephen, pers. comm.). While EU legislation to prevent the movement of listed and protected species like European eel (*Anguilla anguilla*) and sea lamprey into tailrace environments is not yet on statute books, it seems inevitable that it will become an EU-wide legal requirement.

While this paper has focused on the control of upstream movement of fish, the GFFB has also been deployed successfully to prevent the downstream movement of fish at low water velocity (generally less than 0.3m s⁻¹) sites, e.g. [10] where water velocities during tests varied between 0.03 and 0.05 m sec⁻¹. Successful deployment of the GFFB in still waters has also been demonstrated [18]. The success of the deployment of the barrier dispersal system in the CSSC which has an average water velocity of 0.3m s⁻¹ (flow from the Great Lakes to the Mississippi Basin), water conductivities averaging 3500 µS cm⁻¹ and extremely large volumes of water to electrify suggests that they can be deployed in canals globally where river basin connections of this type offer invasive and nuisance fish species access to new environments [10].

The safety of humans and other animals which intrude accidentally or otherwise into the operating zone of a GFFB has always been a priority for the manufacturer and regulators. The maximum pulse width from the POW is 10ms (0.01 sec) and this pulse duration is well below the electrocution threshold for a typical adult and also well below the maximum permitted by UL for a class A ground fault interrupter/typical ground fault interrupter (Lacy [20]).

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References


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