Non-Lethal Electric Guidance Barriers for Fish and Marine Mammal Deterrence: A Review for Hydropower and Other Applications

Carl V. Burger (Senior Scientist), Smith-Root, Inc., Vancouver, WA USA
John W. Parkin (PE; Civil Engineer), Parkin Engineering, Vancouver, WA USA
Martin O’Farrell (PhD), Smith-Root Europe, Dublin, Ireland
Aaron Murphy (PE; Water Resources Engineer), Smith-Root, Inc. Vancouver, WA USA
Jenifer Zeligs (PhD), Moss Landing Marine Labs, Moss Landing, CA USA

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Abstract: Mild fields of non-lethal, pulsed DC electricity have been used extensively in North America and Europe as barriers to block the upstream migration of invasive aquatic fish species. Electric deterrence arrays have also been deployed to guide fish away from hydropower and water intake canals. Successful applications have used an innovative design approach: the Graduated Field Fish Barrier (GFFB). There are 47 GFFB electric arrays in use around the world for fish guidance and deterrence. GFFBs have demonstrated the ability to guide fish away from areas where fish injury potential is greatest. They also offer the potential to keep predatory marine mammals (e.g. Pacific harbor seals and California sea lions) from sensitive “bottlenecks” where fish congregate and from colonizing structures where their presence can cause conflicts. We review the published literature on past deployments of GFFBs for aquatic species deterrence. We discuss the key elements of this innovative technology and why it works. The focus includes examples of graduated-field barriers that have either met deterrence goals or provided “lessons learned” in engineering applications for the hydropower development community. Installations that have deterred Asian and common carp in Chicago, Minnesota and Florida are discussed along with applications that have kept salmonid fishes out of hydropower tailraces in Switzerland and the U.K. Non-lethal electric gradients to safely deter marine mammals in Canada and in the U.S. are also reviewed. One of the highest priorities for hydropower development is the need to safely guide downstream-migrating fishes away from water intakes. An innovative GFFB concept will be presented to address this need. The key may be in combining graduated electric guidance fields with other technologies that promote sensory avoidance stimuli for fish and marine mammal deterrence and guidance.

Introduction
Numerous papers have addressed fish passage issues, fish behavioral exclusion techniques, and fish guidance technologies for the hydropower industry (see for example SNIFFER 2011; Taylor 2011; Coutant and Whitney 2000; EPRI 2003; EPRI 1998; Turnpenny et al. 1998). Such reviews are well beyond the focus and constraints of this presentation. This paper reviews and describes an innovative approach to control and guide fish movements using Graduated Field Fish Barriers (GFFBs). The
use of this technology has been minimally reported in the peer-reviewed literature and there have been few applications within the hydropower sector. Thus, the objective of this paper is to review the pertinent literature on electric barriers for the guidance and deterrence of fish and other aquatic species, and to address potential applications for the hydropower sector.

Since about the mid-1900’s, electric fields in various forms have been evaluated for their ability to block, deter or guide fish movement in both upstream and downstream directions. Electric fields have also been used to contain fish within specified areas. Electric barrier technology has evolved over time, from abrupt deterrence-type fields (which are still applicable in certain applications) to those employing progressively more intense (or “graduated”) fields, often using combinations of waveforms and/or innovative configurations. Currently, 47 GFFB electric barriers are either in use or known to have been used around the world for fish guidance. Yet only three applications have addressed the needs of the hydropower sector.

We summarize what has been learned following the installation of GFFB technology to meet fisheries management, invasive species, and hydropower-related needs for fish passage. We include some recent data on the potential for non-lethal deterrence of marine mammals using GFFB concepts. For many years, downstream fish-guidance applications have remained a priority need and a difficult challenge for natural resource administrators and hydropower-sector managers. We conclude with an innovative concept and some novel ideas for testing new approaches for future hydropower uses, especially for downstream fish guidance.

**Background**

Electric guidance technology appears to represent an under-utilized and undiscovered technology among the hydropower management community. Although used for many different types of applications in fisheries management, there are just a few examples of electric guidance barriers at hydro facilities based upon our review of available literature.
Electric deterrence technology seems to have its earliest origins in the use of alternating current (AC) to keep fish out of irrigation drainage ditches in the Columbia River Basin (Baker 1928). These efforts were unsuccessful and relied on waveforms (AC) now known to increase the potential for fish injury. Unlike AC, pulsed DC (direct current) offers many safety improvements and is far less injurious to fish (Reynolds 1983).

By the late 1980’s a newer concept for electrical guidance was developed, the Graduated Field Fish Barrier (GFFB). Unlike previous electrical barriers, the GFFB (designed and manufactured by Smith-Root, Inc., Vancouver, WA) uses a series of parallel electrodes ... graduated in power intensity ... that are placed perpendicular to stream flow. Using a series of DC pulse generators, each successive pair of electrodes can be independently controlled and each can deliver progressively stronger voltage gradients, thus producing increasingly intense electric fields as fish attempt to move upstream. When fish tire of “fighting the field” and/or turn sideways (to experience the least powerful field alignment), stream flow flushes them downstream to safety before they encounter higher levels of current. Initial studies on the performance of GFFB technology for fish deterrence provide some useful insights. For example, Hilgert (1992) exposed adult coho salmon (*Oncorhynchus kisutch*) to GFFB fields up to 0.9 V/cm for 10-second intervals (far longer than those experienced in usual applications), and found no injuries to adults and no effects on egg viability or development.

**Safety Considerations**

Two published reviews of fish passage technologies have urged caution in recommending electric barriers for fish passage uses (SNIFFER 2011; O’Keeffe and Turnpenny 2005). The latter authors, however, acknowledge the much higher levels of safety that are associated with modern electric barriers, particularly the GFFB. Are the safety concerns warranted? And could such concerns be a factor in the lack of use of electric barriers by the hydropower industry?

Safety is always the priority, but an examination of the facts associated with the historic use of electric fish barriers can help put things into perspective. There has not been a
single case (that we have found) where a serious injury or human mortality has occurred as a result of an electric screen, barrier or GFFB deployment. There have been reports of animals killed by electric barriers at fish hatcheries, and a confirmed report of two humans that floated through an operating electric barrier in a Michigan stream after their canoe capsized, but no injury resulted.

It is perhaps human nature that many of us fear electricity (especially electricity in water). Indeed, people are educated at very young ages about the dangers of electricity and the hazards of electric shock. Yet the statistics on injuries or deaths from the use of electric barriers (or even electrofishing sampling technologies) do not justify extreme levels of concern and fear. Electric guidance technology is not “the hair dryer in the bathtub” that has been popularized in Hollywood movies. Nor is it a dangerous technology when operated properly and safely. However any technology can cause injury or mortality when used in an unsafe manner.

Figure 1 contrasts the outputs of AC and DC electric fields. AC fields are highly injurious because of their rapidly reversing polarities that can damage tissues and cells.
Figure 1. Comparison of alternating (AC) and direct current (DC) electric gradients. AC output is typical of household appliances. The DC field is typical of those used in Graduated Field Fish Barrier technologies, having a pulse frequency of 2 or 3 Hz and a pulse width of 3-5 milliseconds (ms) in most applications. These values can be higher or lower based on needs, species and water conductivities.

Modern electric barrier technology uses pulsed DC waveforms to guide or deter fish swimming behavior. What representatives in the hydropower and related sectors need to know is that electric guidance technology can be used safely in water. Its power levels can be adjusted (either on-site or remotely, using sensors and telemetry), and its outputs can be limited, confined, and/or controlled and directed to safely meet specific fish guidance objectives at levels that are not lethal to either fish or humans.

How Graduated Field Fish Barriers Work
The basic premise of the GFFB is that upstream-moving fish enter the field in alignment with the "head-to-tail" orientation of the electric field generated by the GFFB barrier (Figure 2). The field intensity increases as the fish attempts to move further upstream (to the left in Figure 2). Fish will attempt to find water where the field intensity is lower, and to do this, they learn to turn sideways to the electric field lines. The fish are then swept safely downstream by the water velocity. This is the observed outcome when an upstream-moving fish attempts to challenge a GFFB. (When cross-wise to the field, fish receive little or no effect.)

Figure 2. Electric field lines and orientations of fish as they approach and enter Graduated Field Fish Barrier (GFFB) electrode arrays. Intensity increases as fish attempt to move left, into the field.
Figure 3 shows a detailed concept diagram of these electrical gradients depicting a typical configuration and how fish sense and perceive the deterrence field generated:

**The Graduated-Field Fish Barrier: A Conceptual View of Power Transfer**

Figure 3. Concept diagram of the graduated output of a GFFB electric deterrence array to guide upstream-moving fish into a diversion channel. These applications are often used in fisheries management settings (e.g. to control invasive species or guide fish back to hatchery holding ponds). The gradient (V/cm) increases as fish move upstream.

**Literature Review Results**

Our literature review addresses the publications and reports we found on the use of GFFB electric barriers to guide upstream-moving fish and divert downstream migrants for various fish conservation objectives. In the upstream applications, we summarize the use of electric barriers for three main focus areas: (1) guidance of upstream-moving fish for fisheries management-related outcomes, (2) the control of invasive fish species, and (3) for hydropower uses. Comparatively fewer examples have documented the use
of electric arrays to guide downstream-moving fish and to deter marine mammals but some very noteworthy results are highlighted in the applications we review.

Use of Electric Barriers to Guide and Deter Upstream-Moving Fish

In addition to some early efforts to block or guide fish movements with electricity in the U.S. (Baker 1928; Applegate et al. 1952), several historic attempts were made to influence fish behavior in the U.K., using localized fields of vertical electrodes. Whereas the U.K. efforts (1950’s and 60’s) were unsuccessful (Solomon 1992), those using both AC and DC fields of 1.5 to 2.5 V/cm with pairs of parallel, bottom-mounted electrodes blocked the upstream migration of sea lampreys (Petromyzon marinus) into tributaries of the Great Lakes (Applegate et al. 1952). This historic research in Michigan perhaps provided clues and an indication of promise in graduating the intensity of electric fields.

Other published accounts of the efficiency of electric barriers (to either confine or divert fish) used conventional approaches involving rather abrupt fields of AC and DC electricity. These studies used non-graduated fields that the authors evaluated for an ability to confine marine fish for the fish farming community (Stewart 1981) or to divert fish into traps for tag recovery and population estimation (Palmisano and Burger 1988).

The development of GFFB technology resulted in more focused efforts and greater attention on the use of electric fields to block the upstream movement of invasive species (Moy et al. 2011; Sparks et al. 2010; Clarkson 2004; Swink 1999; Verrill and Berry 1995). Although there are at least four GFFB barriers currently in use at federal fish production facilities in the Northwest (to guide Pacific salmon back to hatchery holding ponds), there are no published data on the performances of these barriers. However, all have remained in use for a decade or more and appear to be meeting intended goals. An agency report (CDFG 1993) describes the use of a GFFB to guide and re-direct migrating fall Chinook salmon (O. tshawytscha) from the San Joaquin River to spawning habitat in the Merced River, California. A report prepared by GREN Biologie (2009) is particularly relevant. It describes the efficiency of a GFFB in keeping salmonids from entering a hydropower tailrace near Geneva, Switzerland.
Examples of Upstream-Guidance Barriers for Fisheries Management Needs: The California Department of Fish and Game installed an electric barrier for fish guidance in the San Joaquin River in 1992 (CDFG 1993). This GFFB guidance array was installed in a 40-m wide, low-gradient reach of the San Joaquin just above its confluence with the Merced River. Barrier effectiveness was evaluated with the aid of a salmon trapping facility 40 m upstream. Goals were to guide Chinook salmon into the Merced (a stream with abundant spawning habitat) and to minimize straying of fish into irrigation canals and areas having no habitat for successful reproduction.

Based on salmon escapement data collected from trapping stations in pre-barrier years, CDFG estimated that 200-300 adult Chinook salmon were straying upstream into San Joaquin-drainage irrigation canals in years before the barrier was installed (an average stray rate of 69%). However, the report states that in 1992, while the electric barrier was in operation, only 11 of 988 migrants (or 1% of fish) were found in upstream areas. This report, and the continued use of GFFB electric arrays for upstream guidance of fish to holding ponds at four U.S. federal salmon hatcheries (Figure 4; no reports or publications available), suggests that electrical barriers can be quite successful in guiding and deterring upstream salmon movements.

Figure 4. Upstream salmon guidance barrier at Abernathy Fish Technology Center (U.S. Fish & Wildlife Service), Longview, WA. These types of barriers (there are four in the Pacific Northwest) guide Pacific salmon back to hatchery holding ponds (into entry channels located downstream of the barriers). The bottom-mounted electrodes (spaced at 1-m intervals) are encased in special concrete, unaffected by debris or sediment.
Because there is a high potential for human (and even animal) interactions at locations such as fish hatcheries (where public visitation occurs on a regular basis), GFFB technology has incorporated several innovations for safety. For example, motion detectors and low-water sensor technologies are used to shut off barrier power automatically when a human or large mammal “target” is detected in close proximity to the array, or when water volumes over the barrier fall below levels that meet safe operating standards. These engineering enhancements (standard for all new deployments) can increase safety margins at fisheries installations where public visitation opportunities exist.

(2) Examples of Upstream-Guidance Barriers for Invasive Species Control: There are at least five comprehensive publications in peer-reviewed journals that describe the in-situ field use of electric barriers to control upstream movement by invasive fish species. A study conducted entirely within a laboratory setting (Dawson et al. 2006) examined both acoustic and electric deterrence arrays to control tank movements of the Eurasian ruffe \((Gymnocephalus cernuus)\). Significant deterrence of ruffe was documented at barrier settings that included pulse widths of 5 ms at pulse frequencies of 6 Hz. In contrast with the many successful outcomes for deterrence of other invasive species with GFFBs (cited below), neither technology was 100% effective in deterring ruffe in this lab application, possibly indicating the need for species-specific research on deterrence settings. A paper by Taylor et al. 2003, however, describes a 57% effectiveness rate in repelling Asian carps with Bio-Acoustic Fish Fence (BAFF) technology alone but noted an 83% level of successful deterrence when a GFFB was combined with a Sound Projection Array-driven BAFF to deter Asian carp movement.

**Carp Control:** An over-abundance of common carp \((Cyprinus carpio)\) and another fish species prompted an investigation of the effectiveness of a GFFB electric barrier to prevent these fish from entering the Heron Lakes watershed in Minnesota (Verrill and Berry 1995). The authors of this peer-reviewed research tagged and released 1,600 fish downstream of the electric barrier. Of those 1,600 dart-tagged individuals, no tagged fish were among the 3,367 fish caught upstream of the electric barrier in this 2-year
study. The authors concluded that the barrier reduced populations of invasive fish and could find no evidence that tagged fish moved upstream of the GFFB electric barrier into Heron lakes. As noted by these authors, the Heron Lake barrier was installed in 1991. It has been operating since that time and continues to keep the lake free of undesirable species.

**Sea Lamprey Control:** The control of upstream sea lamprey spawning migrations has been a priority and focus of several fish management agencies for over 60 years. Swink (1999) describes the effectiveness of a GFFB electric array to block the movements of spawning-phase sea lamprey adults into the Jordan River, Michigan. Swink marked a few thousand sea lampreys. He released 2,093 animals upstream of the barrier (to determine recapture efficiency) and 1,194 specimens downstream of the array (to evaluate electric barrier effectiveness). After the appropriate deterrence setting was established for this GFFB barrier (10 ms pulse width, pulse frequency of 10 Hz), none of the 1,194 tagged animals were recovered upstream of the barrier.

Swink mentions the upstream deterrence of desirable salmonids as a potential drawback when the barrier is in operation for sea lamprey control. However, he points out that his mark-recapture study “provides convincing evidence that the pulsed DC electrical barrier was fully effective at blocking migrations of spawning-phase sea lampreys in the Jordan River,” that it should be applicable for use in other such streams, and that it reduces a reliance on chemical lampricides for lamprey control. Rozich (1989) conducted a similar but unpublished study on the control of sea lampreys with an electric barrier in the Pere Marquette River. Like Swink, he documented the successful prevention of upstream migration by lampreys but in this case, simultaneous downstream migration of desirable salmonid species was also accommodated (without injury).

**Non-Indigenous Fish Control:** Some of the first GFFB electrical barriers ever produced were installed into Central Arizona Project aqueduct canals to deter upstream movements of several non-indigenous fish species (Clarkson 2004). These barriers
(two were installed in Salt River canals in 1988; a third in the San Carlos Irrigation Canal in 1990) were put into place to keep non-indigenous and invasive fishes out of the Gila River drainage. The sizes of these canals range from 15 to 30 m in width, 1 to 3 m in depth, and they carry up to about 36 m$^3$/s at maximum flows.

These GFFB deterrence barriers in Arizona (though “old” in technology terms) are still in use some 25 years after installation. However, and as pointed out by Clarkson (2004), their operating histories include a series of documented problems that make for a useful example of “lessons learned.” The list includes numerous power outages that have resulted from mechanical failures and human errors. The operational issues have included frequent lightning strikes (that have damaged barrier electronic components), insufficient fuel in power generators, and insufficient or inadequate maintenance of the barriers by the multiple parties that operate them. Despite the installation of a Fish Barrier Telemetry Control System (FBTCS) to automatically monitor for outages, activate alarms, and allow for remote power adjustments, simple accompaniments (such as servers and modems supplied by local telephone companies) have failed on several occasions.

Clarkson reported a barrier “down time” of just 100 hours of operation for the 12-year period (1988-2000) of his review (representing an outage frequency of less than 0.001% during the review timeframe). While such a low incidence of barrier outage may seem inconsequential, it is too great when preclusion of upstream migration by invasive species is an absolute requirement. Even with inclusion of the FBTCS system to automatically monitor for alarms and report outages by modem or phone, the original technology is outdated and in severe need of upgrades with more modern pulse generators.

Mechanical and human oversight issues can arise when multiple parties are involved with operating and maintaining this technology. It is not that these electric barriers cannot stop invasive fish per se, but rather it has been an administrative challenge to keep them properly maintained and running.
Barriers for Asian Carp Control in Chicago: Following the installation of a successful demonstration barrier in the Chicago Sanitary and Ship Canal in 2002, two permanent deterrence barriers have since been deployed at this site. They provide redundant backup deterrence to prevent invasive Asian carp (*Hypophthalmichthys* spp.) from entering the Great Lakes. Moy et al. (2011) provide substantial background information on the reasons and considerations for deploying electric deterrence barriers in the Canal.

These barriers (now operating at high levels and pulse frequencies of 15 Hz to control all fish life stages) are the world’s largest. They electrify a complex channel (having occasional flow reversals) that is 49 m in width and up to about 8 m in depth. The barriers use state-of-the-art, remote monitoring technology and sensors to adjust power settings automatically whenever water conductivities and conditions change.

The Chicago Sanitary and Ship and Canal is heavily used by frequent barge and tug traffic on a daily basis. Numerous metal-hulled boats traverse the live electric fields. There is no effect on either boats or occupants because no “electric potential” is created. Metal-hulled craft have the same potential as the field itself and non-conductive hulled craft are insulated.

Sparks et al. (2010) evaluated the performance of the initial electric deterrence barrier in Chicago. They implanted radio tags in 130 common carp surrogates, released these fish downstream of the barrier, and tracked fish movements to evaluate barrier performance. Over their 4-year radio-tagging study, Sparks et al. documented a single specimen (out of 130 tagged fish) immediately upstream of the original barrier in April 2003. Because the transmitter did not exhibit any further upstream movement, the researchers deemed this to be a dead fish that was possibly swept upstream by a passing barge. (The authors also mention that waterway bypasses are known to exist including floods and spillover events in Canal tributaries that could explain the occasional detections of “environmental” DNA evidence implying carp presence in upstream locations.) Also, there is recent, growing evidence that improper fish stocking
in ponds (for recreational fishing) may have led to an unintentional introduction upstream of the electric barriers.

(3) Examples of Upstream-Guidance Barriers for Hydropower-Related Uses: Of the three examples of electric barriers used for fish deterrence by hydropower operators, there are no published papers on the efficiencies of a tailrace barrier to keep fish out of turbines in Beeston, U.K. (but published, anecdotal performance data exist). However, reports are available on the electric barrier efficiencies on the Puntledge River in British Columbia (Bengeyfield 1990) and a tailrace barrier in Switzerland (GREN Biologie 2009).

**The Beeston Example (Unpublished):** In the Beeston application, a GFFB deterrence array was fitted into the power plant’s draft tubes to prevent fish entry during hydropower generation. O’Keeffe and Turnpenny 2005 provide some anecdotal information on this barrier and “a lesson learned.” When originally commissioned, this “run-of-river” plant on the River Trent at Beeston turned off its GFFB electric outfall screens whenever the plant shut down. Residual flows from the draft tubes attracted a few large fish that were subsequently injured at startup. This issue was resolved by keeping the electric barrier technology powered even when the plant was not fully operational. O’Keeffe and Turnpenny went on to report that the barrier then worked well to deter upstream migration by salmonids and other fish species at Beeston. It is important that administrators keep these deterrence barriers energized even during periods of non-power generation. Doing so minimizes potentials for unwanted draft tube entry by resident fish.

Insights from the Beeston experience may represent an opportunity for Columbia River Basin hydropower operators (to keep fish out of draft tubes during de-watering for maintenance episodes, and preclude the stranding and mortalities of sturgeon and salmonids that can regularly occur after such draft-tube dewatering). Over 1,000 steelhead trout (*O. mykiss*) were entrained and killed in the draft tube at Dworshak Dam and Reservoir, Idaho during routine dewatering for maintenance in 2010 (Columbia
An example of a barrier designed to preclude fish entry into hydropower draft tubes is presented in Figure 5. These types of electric deterrence arrays can be programmed to turn on in synchrony with de-watering maintenance, potentially saving fish from lethal encounters and hours of staff time in removing trapped individuals.

Figure 5. Design concept for a hydropower draft-tube with GFFB deterrence barrier to preclude fish entry either during power generation or when facilities are shutdown for de-watering and maintenance.

*The Puntledge River, B.C. Penstock Barrier (Unpublished)*: This application attempted to use a GFFB electric barrier to guide coho salmon smolts (*O. kisutch*) to a downstream bypass channel in the Puntledge River, B.C. (and prevent their entry into a hydropower penstock intake). Bengeyfield (1990) evaluated captures of downstream-moving smolts entering both the 5.8-m bypass diversion channel (back to the river) and the penstock intake. During the study, the river typically carried 31 m$^3$/s (and up to 170 m$^3$/s at flood stage). The Puntledge Generating Station was designed to produce up to 24 MW of power.
Bengeyfield reported that sonics, lights and chain curtains failed to reduce smolt mortalities in 1989. The electric barrier also failed to divert substantial numbers of smolts back to the river. Bengeyfield concluded that the failure of the diversion barrier resulted from some combination of an incomplete electric field, an unsuitable flow regime (approach velocities may have been too high), and an unsuitable bypass structure to deter fish use. The lessons learned? After reviewing this 1990 report, other factors certainly contributed to the barrier’s failure: the array was configured perpendicular to river flow (rather than angled for enhanced fish diversion) and the approach velocities were too high (up to 1 m per second). In addition, there were reports of metal in the streambed from historic bridge demolition in the area (which may have affected the electric field’s performance) and there was insufficient distance and angling of the barrier to reduce the approach velocity effect and properly divert downstream movement of fish.

The Centrale Hydroelectrique de Vessy Hydropower Example: The effectiveness of a hydropower-tailrace electric barrier was summarized in a final report for a power generation facility at Vessy (near Geneva), Switzerland (GREN Biologie 2009). The GFFB electric deterrence array was installed in the tailrace of Centrale Hydroelectrique de Vessy in 2008 (Figure 6). The consultant’s report was translated and approved by the power authority. Key points in their report include:

- The fish, which moved upstream using a migration route situated along the left bank, did not enter the tailrace and were effectively guided along the bed of the River Arve. In fact, whether these fish were fall trout or spring barbels, a comparison of fish actually present in the tailrace to the catch in the traps of both fishways shows that the electric barrier played its role perfectly and migrating spawners did not have a propensity to wander (at a higher rate) into the tailrace.

- None of the 339 brand-marked trout put into water of the River Arve in mid-October 2008 ... just downstream of the plant ... were found in the tailrace one month later, while in this interval 16 of the brand-marked trout were passed by the two fishways. These results confirmed that the electric barrier demonstrated good efficiency in moving branded trout upstream and that none ended up becoming trapped at the foot of the hydroelectric plant.
Despite the capacity of the tailrace to provide fish habitat, very few fish were found during electrofishing. The effectiveness of the electric barrier system explains the insignificant presence of fish observed in the tailrace compared to the much higher fish numbers found in the River Arve at a point directly proximal to the hydropower station.

Figure 6. The tailrace GFFB electric deterrence array at the Vessy (Switzerland) hydroelectric power plant. The barrier has successfully deterred fish from moving upstream into the tailrace from the River Arve.

This report provides important insights as to how Graduated Field Fish Barriers can help the hydropower industry with its fish passage issues and with fish protection and conservation priorities.

Use of Electric Barriers to Guide and Deter Downstream-Moving Fish
Protection and diversion of downstream-moving fish at hydropower and other water withdrawal facilities has proven to be a serious challenge, even for the most astute water resource engineers. A variety of screens and techniques have been designed and evaluated in attempts to guide fish safely away from hydropower tailraces and irrigation diversion and water intake canals. Angled, louvered, inclined and Eicher-type screens have been evaluated extensively for downstream fish diversion. Despite evidence demonstrating success, approaches using electric fields to influence fish
behavior and guide or divert downstream movement have received comparatively little attention (EPRI 2002; EPRI 1998). Literature searches produced four studies that address and evaluate *downstream fish guidance* using GFFB electric deterrence arrays: Barwick and Miller (1990); Demko et al. (1994) Maceina et al. (1999) and Savino et al. (2001).

*The Duke Power Study on Upstream and Downstream Fish Deterrence:* In early tests of the effectiveness of a GFFB to block five species of fish during simulated hydropower-related flow protocols, Barwick and Miller (1990) evaluated fish responses in both upstream and downstream deterrence scenarios. After demonstrating a randomized distribution of fish when no electric field was present, these authors conducted tests in a canal using GFFB gradients that gradually increased in intensity from 0.5 to 3.0 V/cm. With fish kept at the canal’s east end, fish response was determined during simulated non-generation of power (the no-flow control), power generation (the upstream deterrence tests when flows were introduced from the west) and power generation pumping (the downstream deterrence tests when flows entered the canal from the east). About 1,200 L of water per minute were introduced during the power generation and pumping trials to induce velocities from 0.15 to 0.2 m per second across the GFFB.

The simulated upstream tests conducted by Barwick and Miller demonstrated fish deterrence levels of 97% (during both power-generation and non power-generation simulation periods). They also documented a fairly high level of downstream fish deterrence (84%) in these hydropower-related simulations. The authors point out that this slight reduction in downstream effectiveness “may have resulted from a fright response” when water pumps turned on, rather than ascribing the performance reduction solely to a GFFB-related efficiency issue. They concluded that GFFB technology was successful in blocking the movements of five fish species during the modes of operation associated with hydropower generation in their demonstration study.
The Sacramento River (Wilkins Slough) Downstream Diversion Canal Barrier: Wilkins Slough (Reclamation District 108) is used to divert Sacramento River water for irrigation purposes in California. The goal was to use an electric barrier to reduce entrainment of ESA-listed Chinook salmon while still allowing water diversion to occur. In 1992 and 1993, two technologies were tested (an acoustic deterrence device and a GFFB electric deterrence array) to evaluate their fish deterrence potentials (Demko et al. 1994).

Study results showed inadequate performance by the acoustic technology. However, the GFFB reduced entrainment of marked juvenile Chinook salmon by 79%. This level was deemed insufficient by NOAA fisheries scientists who required a 95% reduction to meet Biological Opinion and Endangered Species Act criteria. The 79% entrainment reduction, however, was achieved despite the use of an undersized electric array positioned too close to the diversion canal entrance where Sacramento River water was flowing directly at the mouth of the canal. The lessons learned? Use properly sized electric arrays, position them further upstream in these situations (to affect behavior well before fish are carried directly into a pump station or diversion canal), and try to reduce the approach water velocities at the diversion entrance.

The Lake Seminole Fish Retention Barrier: This research evaluated the feasibility of retaining triploid grass carp (*Ctenopharyngodon idella*), a desirable fish species, with a GFFB at the outlet of Lake Seminole, Georgia. The goal of this 2-year study (by Maceina et al. 1999) was to demonstrate whether radio-tagged and coded wire-tagged grass carp could be retained in embayments of Lake Seminole to crop invasive vegetation. The study compared two conventional weirs (v-shaped and gated) with the performance of a GFFB electric array to prevent fish escapement from the lake. Results suggested that up to 42% of the radio-tagged carp escaped through the v-shaped barrier and 35% from the gated barrier, with an overall 68% escapement rate of coded wire-tagged fish through conventional weirs (as confirmed from electrofishing surveys in the outlet river).
After the v-shaped barrier was outfitted with the GFFB however, no verified escapes occurred (with the exception of one radio-tagged individual that could not be accounted for). Maceina et al. (1999) concluded that the electric barrier was successful in retaining grass carp in the embayment. This barrier has been documented to be effective for fish retention and has remained so since installation.

**Efficiency of an Electric Barrier to Control Downstream Goby Deterrence:** In attempts to evaluate whether electric barriers can block the downstream movements of invasive round goby (*Neogobius melanostomous*), both lab studies (to determine appropriate voltage gradients) and field research (to obtain in-situ results) were conducted. The goal of this research (published by Savino et al., 2001) was to determine the effectiveness of a graduated electric barrier in blocking downstream goby movement in the Shiawassa River, Michigan. Gradients in the strongest portion of the electric deterrence field approximated 5 V/cm. The GFFB was positioned on the stream bottom in a location that was 20 m wide and from 0.5 to 1 m deep. Savino et al. 2001 determined that the simulated laboratory barrier was about 80% effective in repelling round goby but “almost 100% effective in deterring round goby downstream movement” during the scale-up river study of the electric barrier. Apparently, only dead round goby were found downstream of the barrier. The authors recommend combinations of electric barrier and other deterrence technologies for downstream fish deterrence in large rivers having appreciable stream flow.

**Use of Electric Barriers to Guide and Deter Marine Mammals**

Populations of California sea lions (*Zalophus californianus*) and Pacific harbor seals (*Phoca vitulina*) have increased exponentially in U.S. waters since passage of the Marine Mammal Protection Act. These increases have resulted in high levels of riverine predation on sensitive fish species in the Pacific Northwest, complicating population recovery efforts for the region’s fishery managers. Growing numbers of marine mammals also damage docks in boat mooring basins, posing challenges for harbormasters. Smith-Root developed a novel concept to control marine mammals using non-lethal, GFFB electric gradients to deter their foraging behaviors in rivers and
deter their presence on docks and piers, where animal/human use conflicts typically occur. A series of studies and tests (summarized below) have been conducted since 2007 to assess the feasibility of developing guidance technology for marine mammal deterrence in the wild. A published study (Forrest et al. 2009) describes a working technology now in use for marine mammal deterrence in the Fraser River, Canada. The following is a summary of various non-lethal, electric barrier approaches deployed and field-tested over the past few years:

**Deterrence Tests on Captive Harbor Seals, Vancouver B.C. Aquarium (2007):** This study comprised the first-known tests of the effects of a non-lethal, electric deterrence field on marine mammals. In partnership with scientists and engineers from the Department of Fisheries and Oceans Canada, Pacific Salmon Commission, and Smith-Root, two captive harbor seals were exposed to gradually increased voltage gradients in one of the Aquarium’s large swim tanks where animals were pre-acclimated. The underwater deterrence field was limited to the far end of the tank. The first harbor seal was deterred from reaching the end of the tank in four of four trials. The second animal was deterred in 18 of 18 trials. Both harbor seals demonstrated extreme sensitivity to an underwater field of pulsed DC electricity, at levels below what are now known to affect most species of fish. No animal injuries resulted (according to an attending marine mammal veterinarian) and exposed seals fed normally after all trials.

**In-River Deterrence Tests on British Columbia Harbor Seals (2007 and 2008):** Based on the successful outcomes in the swim-tank studies above, a deterrence barrier was placed *in-situ*, into the Puntledge River near Courtenay, B.C. Initial 2007 trials demonstrated immediate deterrence of harbor seals as they swam upstream to forage on salmon juveniles during an evening high tide. A field of just 0.3 V/cm (about 50 V) at a frequency of only two pulses per second (2 Hz) caused five seals to vacate one of their favorite salmon predation areas on the first evening’s tests in the Puntledge River. The following evening, the same non-lethal field prevented about 12 animals from accessing this known predation area (situated under a bridge, where deck lighting illuminated their prey). Seal deterrence reactions were immediate.
More comprehensive assessments were implemented in 2008 trials in the Puntledge River. Different electric arrays were evaluated, and various field strengths examined. With many more animals present, some challenges were encountered: embedded stream-bottom metal may have “shorted the field” and maximum spring tides in the test area (only 8 km upstream of the estuary) weakened the field in a few locations, permitting upstream access by 3-4 seals. However, the GFFB electric deterrence barrier still blocked upstream access by 79% of the seals observed in these trials.

**Seal Deterrence Using Electrified, Test-Fishing Gillnets in the Fraser River, B.C. (2008):**

Seal predation on returning adult salmon had become a serious problem in the Fraser River B.C. over the past decade. Foraging seals were removing salmon from test-fishing gillnets operated by the Pacific Salmon Commission each summer (to determine the strength of the annual salmon runs for in-season management purposes). In addition, seals were damaging the test gillnets. In the Commission’s study, half of a 100-fathom-long, test-fishing gillnet was electrified with GFFB deterrence technology while the other half served as the untreated control. During 30 days of continuous test fishing, the electrified end caught four times as many salmon as the untreated control end (where seals chose to forage and reside). Results of this highly successful demonstration project were published by Canadian scientists in the North American Journal of Fisheries Management (see Forrest et al. 2009). This deployment was so successful that it has become a mainstay technology of the Commission each summer, to keep predatory harbor seals from attacking test-fishing gillnets in the Fraser River.

**Deterrence Tests on California Sea Lions at Moss Landing Marine Labs (2008):** Trials on California sea lions (conducted with Dr. Jenifer Zeligs, an internationally recognized expert on marine mammal behavior) also highlighted the extreme sensitivities of pinnipeds to non-lethal electric gradients (Zeligs and Burger 2008). Following tests to determine field levels that animals could discern, deterrence trials were conducted on four California sea lions. Successful deterrence was achieved in all trials, even when a favorite prey item (herring) was introduced on the far side of the deterrence array. Field trials were conducted at levels using about 50 V at a pulse frequency of just 2 Hz.
California sea lions were successfully deterred even when food was present. Video results of this research may be found at this link:

**Deterrence of California Sea Lions from a Marina Dock (2012):** Using a highly innovative waveform of low-energy electric current, these trials documented the ability to deter and prevent sea lions from using a California marina dock that had been used regularly by hundreds of animals over the past few years. A video link provides the results:  [http://www.smith-root.com/videos/moss-landing-sea-lion-exclusion-test/](http://www.smith-root.com/videos/moss-landing-sea-lion-exclusion-test/)

Some 1,100 video-recorded deterrence examples were documented with no successful repopulations (unless an animal was on a corner of the array, touching just one of its paired electrodes). This novel array could not be felt by most human subjects yet it kept sea lions from “hauling-out” on the dock surface. This technology will have meaningful applications among hydropower users and other energy producers who wish to exclude marine mammals from project-related infrastructure (see Figures 7 and 8).

![Figures 7 and 8. The Moss Landing Visitor’s Dock before (left) and after (right) one of its segments was equipped with an electric deterrence array to prevent California sea lion repopulation. Over 1,100 video-recorded observations confirmed that sea lions would not reside atop a dock segment energized with a novel, non-lethal waveform.](image)
Table 1 summarizes some of the salient findings and conclusions from evaluations of Graduated-Field Fish Barriers in both peer-reviewed publications and agency reports.

<table>
<thead>
<tr>
<th>Barrier Location</th>
<th>Citation</th>
<th>Author-Reported Conclusions on GFFB Efficiencies</th>
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</thead>
<tbody>
<tr>
<td>Heron Lake MN (U)</td>
<td>Verrill &amp; Berry 1995</td>
<td>“None of 1,600 tagged fish were among the 3,367 examined above the barrier.”</td>
</tr>
<tr>
<td>Shiawassee R. MI (D)</td>
<td>Savino et al. 2001</td>
<td>“The only marked round goby found below the barrier were dead.”</td>
</tr>
<tr>
<td>Lake Seminole GA (D)</td>
<td>Maceina et al. 1999</td>
<td>“After (the GFFB) electric barrier was in place, no verified escapes occurred.”</td>
</tr>
<tr>
<td>Jordan River MI (U)</td>
<td>Swink 1999</td>
<td>“No unmarked and none of the 1,194 tagged lamprey were found above the barrier.”</td>
</tr>
<tr>
<td>Chicago Ship Canal IL (U and D)</td>
<td>Sparks et al. 2010</td>
<td>“Of 130 radio-tagged carp, one (a dead fish?) was found above the electric barrier.”</td>
</tr>
<tr>
<td>Fraser River B.C. (U)</td>
<td>Forrest et al. 2009</td>
<td>The electrified gillnet caught 4x more salmon than the untreated control where seals resided.</td>
</tr>
<tr>
<td>San Joaquin R. CA (U)</td>
<td>CDFG 1993</td>
<td>Only 1% of fish were observed upstream of the barrier.</td>
</tr>
<tr>
<td>Wilkins Slough CA (D)</td>
<td>Demko et al. 1994</td>
<td>“Downstream juvenile Chinook entrainment (from Sacramento River) was reduced by 79%.”</td>
</tr>
<tr>
<td>Vessy Switzerland (U)</td>
<td>GREN Biologie 2009</td>
<td>“None of 339 marked trout were found in the hydropower tailrace after GFFB installation.”</td>
</tr>
</tbody>
</table>

Table 1. A summary of some of the results of studies and evaluations conducted on Graduated-Field Fish Barriers from both peer-reviewed publications (the first six entries) and agency reports. Barriers designed to deter upstream-moving fish are designated (U) while (D) denotes barriers used to guide or control downstream-moving fish.
Discussion

What do we know about the performances of electric deterrence barriers, and what does our review indicate?

First and foremost, there is no question that electric barriers (especially GFFB’s and their telemetry monitored alarm and water quality sensory systems) can successfully guide, direct and deter the upstream migrations of fish to meet fish passage goals — whether for fish management, invasive species control, or hydropower-related conservation. Our review of existing literature supports this conclusion. Many successes were highlighted in our review. Results show that electric barriers can safely guide, control or deter upstream fish migrations in many different applications, including those required for hydropower application. These upstream-deterrence control barriers can be quite effective in environments that range from small culverts to transportation canals and major rivers. Our review also underscored some noteworthy successes in the use of GFFB electric deterrence barriers to guide or divert downstream-moving fishes. Despite the challenges encountered in the Wilkins Slough (RD 108) study by Demko et al. 1994, the electric barrier successfully diverted 79% of the juvenile Chinook salmon that would have otherwise become entrained into the irrigation canal. Also, and as Savino et al. 2001 and others have demonstrated, GFFB electric barriers have been successful in guiding or diverting downstream-moving fish where approach velocities are generally less than about 0.3 m/s.

Second, the testing and use of innovative electric fields has documented noteworthy success in the deterrence of marine mammals (e.g. sea lions and seals) in either keeping them away from fish predation areas, or preventing their “haul-outs” on marina infrastructure.

In regards to fish passage uses, are there ways to improve upon these successes? Where does the technology go from here? Much has been learned recently from studies that have evaluated electro-anesthesia devices for fish sedation purposes (Trushenski et al. 2012; Zydlewski et al. 2008;). While such studies may not appear to
be at all related to fish passage needs and guidance technologies for hydropower or other uses, results from these highly controlled studies of fish response to electric fields provide many useful insights for the next generation of GFFB electric deterrence technologies. The innovative concepts below have evolved from, and are in large part a result of some of the highly controlled studies and research on fish (and marine mammals) exposed to various bi-directional fields of pulsed DC in sedation and deterrence research. They are also the result of some recent work on “appetite suppression” and avoidance responses observed among electroshocked predatory fish, and other various engineering enhancements to GFFB technology.

The Innovations

GFFB technology has evolved considerably since the first graduated-field electric fish barriers were installed for invasive fish control in Arizona (1988). Innovations include:

- The addition of Fish Barrier Telemetry Control Systems (to monitor operations remotely and make real-time adjustments to outputs based on perceived conditions);
- “Parasitic electrodes” to help shape fish deterrence fields;
- New and variable types of pulsed waveforms;
- Bi-directional fields where pulses are emitted in alternating “x” and “y” directions;
- Inclusion of sensors that monitor conductivity and water volume changes to adjust pulse width and power outputs automatically;
- Technology to sequence electrode outputs and further graduate field effects;
- “Sweeping fields” using short electrode arrays to force movement into specific areas;
- Applications to randomize power outputs at specific electrode locations;
- Motion and low-water sensing applications to turn barriers off when surface movements (an animal or a human presence) are detected;
- Fields that result in “appetite suppression” among predatory species; and
- Highly novel waveforms for marine mammal deterrence needs.
Many of these innovations (sensors and remote monitoring systems) are available as either standard or custom designs in new versions of GFFBs. Others (e.g. new waveforms) need additional lab engineering and testing. What does the future hold?

A new concept is being developed for use in barriers to divert downstream-moving fish. This priority (downstream guidance: the “Holy Grail” in fish passage applications?) is perhaps the most needed by the hydropower and fisheries management sectors. The vision is for an angled series of downstream-oriented electrodes to nudge fish around and away from intake canals. The electrodes can be either surface-suspended or bottom-mounted. This approach could be combined with additional technologies and stimuli (e.g. cover, water flow manipulations, other forms of sound and/or light, etc.) to induce a rapid “fish-scaring” deterrence response among downstream migrants to promote their movement away from an intake canal during migration. The concept is depicted in Figure 9.
Figure 9. Innovative concept for diverting downstream-moving fish away from water intakes. Downstream-angled electrodes are envisioned with graduated field outputs to nudge fish away from intake canals. Secondary electrode arrays can be added to the canal proper. Arrays can be individually sequenced or operate randomly. Additional technologies (cover, upstream flow reductions, etc.) could be combined with GFFB technology to enhance efficiencies on a site-specific basis.

Like most technology in use today, the Graduated Field Fish Barrier has undergone its own level of evolution and change via new and enhanced waveform outputs, potential combinations of polarity, and novel orientation applications including sequenced outputs. These technologies and applications are worthy of scrutiny by the hydropower sector for possible use in minimizing and/or eliminating impacts to fish in tailraces and intake canals where their presence must be precluded. Consistent with the recommendations made by others for fish passage screening research (e.g. SNIFFER 2011), studies are needed to assess the best technologies and ways to preclude fish from entering hydropower tailraces and turbines. GFFB technology could provide a very useful tool for resource managers in guiding and controlling the movements of fish in either upstream or downstream settings, but test facilities and funding must be obtained to evaluate the most promising options and create approaches for success.

References


Author Biographies

Carl Burger has led the Science Department at Smith-Root, Inc. (Vancouver, WA) since 2007, where he coordinates research and oversees fish and marine mammal behavioral guidance applications. He spent a previous 31-year career with the U.S. Fish & Wildlife Service as a Pacific salmon research scientist (Alaska), a science center director (Washington), and a recovery plan administrator for listed Atlantic salmon (Maine). His fisheries background includes research and publications on management-related issues and salmon population dynamics. He served as President of the American Fisheries Society from 2000-2001.

John Parkin (P.E.) is President of Parkin Engineering, Vancouver, WA. John is a consulting civil and structural engineer who specializes in producing custom engineering designs for graduated field fish barriers, for various fish guidance and deterrence applications, and for associated construction projects. His background includes substantial engineering collaboration on various bridge and building project designs on a global basis.

Martin O'Farrell (PhD) is a Fisheries Scientist with specialties in fish passage and fisheries management, especially for the hydropower and hydroelectric sectors. He represents Smith-Root Europe (Dublin, Ireland). Martin has nearly three decades of expertise with Atlantic salmon and sea trout management, with particular reference to the use of electric fields for guiding and/or sampling fish populations in rivers, lakes and streams. He is a specialist in the use of Graduated Field Fish Barriers for fish guidance applications throughout Europe.

Aaron Murphy (P.E.) is a Water Resources Engineer for Smith-Root, Inc., Vancouver, WA. He has worked on various engineering projects in Australia, the Middle East, Scandinavia and North America. His areas of expertise include river modeling and analysis, flood, sediment and erosion-control engineering, and surface water hydraulics and hydrology. His expertise is fundamental to the implementation of graduated-field, electric fish barrier projects.

Jenifer Zeligs (PhD) is an internationally recognized expert in marine mammal behavior and physiology. Jenifer has over 30 years experience in the training, behavior and husbandry of a wide array of marine mammal species. She has served as head trainer, senior trainer and training consultant for various research projects involving marine mammal behavior and physiology. Jenifer is the principal global consultant on projects that employ non-lethal electric deterrent technologies for marine mammal protection and conservation.