AFS 150TH ANNIVERSARY CELEBRATION

Development of Electrofishing for Fisheries Management

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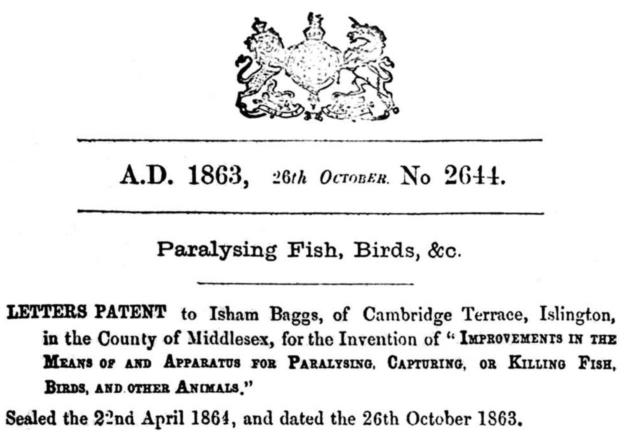
Electrofishing, broadly defined as the use of electricity to capture or control fish, was envisioned in an 1863 British patent application by Isham Baggs. Not until the 1920s, when large, stationary generators were available, did electrofishing applications (i.e., fish barriers) begin. After World War II, applications of electrofishing for fisheries management accelerated in diversity and portability. As the American Fisheries Society celebrates 150 years of dedication to aquatic resource conservation, our aim is to document the development of electrofishing for fisheries management in North America during the same period. Major management objectives comprise the topics in our article. While electrofishing has become a staple in fisheries management for conducting a wide range of applications such as population assessment and eradication of nuisance species, electrofishing use and equipment has evolved, particularly in response to human safety and fish welfare.

INTRODUCTION

Electrofishing may be broadly defined as the use of electricity to capture or control fish. The concept began on October 26, 1863, when Isham Baggs of Islington, Middlesex County, England, applied for a patent entitled *Improvements in the Means of and Apparatus for Paralysing, Capturing or Killing Fish, Birds and Other Animals* (Baggs 1863; Figure 1). Mr. Baggs was a visionary, proposing to use a battery to, among other intents, capture fish with electrified hooks, harpoons, and "metal-sheathed" boats. He even proposed using lenses of the gemstone tourmaline to polarize light for improved vision into water. His patent came among a flood of proposals for various applications of electricity as the world embraced this new technology. Despite the rapid pace of electrical discoveries during the first 6 decades of the 19th century, the Baggs patent was unfulfilled because the batteries then available could not produce sufficient energy to meet the proposed tasks.

Not many years later, during the Second Industrial Revolution (1870 to 1914, the beginning of World War I), motor-generated electricity was developed in the form of stationary industrial generators. These devices produced sufficient energy to capture or control fish in freshwaters. The intent of the Baggs patent was finally achieving reality.

In the 150 years since the beginning of the American Fisheries Society, our profession has made many developments to conserve and protect aquatic resources and the environment. In this article, we summarize the development of electrofishing to meet fisheries management objectives. For this purpose, the paper is organized by management objectives: electrofishing equipment and safety, fish deterrence and guidance, fish population assessment, fish eradication and abundance reduction, standardized fish sampling, fish welfare and handling, and electrofishing equipment manufacturers. Although some of our discussion includes progress in other countries, we have focused on fisheries management in North America.


A.D. 1863, 26th October. No 2644.

Paralysing Fish, Birds, &c.

LETTERS PATENT to Isham Baggs, of Cambridge Terrace, Islington, in the County of Middlesex, for the Invention of "Improvements in the Means of and Apparatus for Paralysing, Capturing, or Killing Fish, Birds, and other Animals."

Sealed the 22nd April 1864, and dated the 26th October 1863.

Figure 1. Header of the 1863 patent application for electrofishing (and other purposes) by Isham Baggs (Baggs 1863).

ELECTROFISHING EQUIPMENT AND SAFETY

This story will sound familiar to older biologists who began their careers in the 1950s and 1960s. Imagine an electrofishing jon boat with no safety railing or safety switches. Alternating current (AC) is supplied directly from a 240-volt generator to the water via house-construction wiring and copper pipe electrodes suspended from two lengths of lumber extending from the bow. The emergency cut-off is a piece of rope tied to the generator kill switch and the other end within reach of the boat driver. This was the contraption that the senior author used for sampling as a graduate student. Dumb luck and youthful enthusiasm were requisites for survival in those days!

Electrofishing is hazardous work; it requires dependable equipment and a safety-conscious attitude. As a profession, we have experienced a fascinating interaction between fishery biologists and electrical engineers. Preceded in the 1930s by German scientist Franz Hager (1934; summarized by Shetter 1938), who used a portable generator for fish capture, the portability of electrofishing accelerated in the 1940s, when U. S. biologists developed the electric seine and handheld anode (positive electrode) systems using bankside generators (e.g., Haskell 1940; Haskell and Zilliox 1941; Shetter 1948). The electric seine was not a capture device; it was used to "herd" fish to a block net for capture. Output control was quite restricted, usually just a rheostat to vary electric current via control of circuit resistance. A precursor of modern pulsed direct current (DC), "interrupted DC," was evaluated as an alternative to continuous DC by another German, Kurt Smolian (1944; as described by Rayner 1949). The waveform was created by lifting a handheld, energized anode out of the water and submerging it again at intervals of 1–2 seconds. In doing so, he found that fish would swim more readily to the anode compared to taxis under continuous DC. In the 1950s, electronic controlled pulsed DC was being actively evaluated and used by fisheries managers (Haskell et al. 1954; Haskell and Adelman 1955). These developments were accompanied by construction of the first electrofishing boat, which served as the pattern for today's boats (Larimore et al. 1950; Figure 2), and backpack units (Haskell et al. 1954). Commercial manufacturing began in the 1960s, giving rise to safer, more reliable equipment.

However, company engineers tended to work in isolation from biologists, who were their customers. Biologists worked with equipment they understood poorly. In the late 1960s and early 1970s, engineers in academia began to collaborate with biologists in the development of boat and backpack units based on research under field conditions (e.g., Novotny and Priegel 1971, 1974). Biologists began conducting their own studies of electrofisher output to understand how to use them more effectively (e.g., Miranda and Spencer 2005; Martinez and Kolz 2013; Dean et al. 2019). Today, engineers and biologists work together to produce safe, effective, and up-to-date equipment.

Figure 2. The first conventional electrofishing boat. Designer Larimore (right) drives the boat while co-author Durham (left) uses a dip net to capture fish (Larimore et al. 1950). Image courtesy of *The Journal of Wildlife Management*

"If a serious accident occurred, could my operation withstand independent scrutiny?" That is a self-help question that requires serious introspection. As biologists, we all tend to operate under the mantra "Get 'er done" and safety concerns may take a "back seat" in priority. However, agencies and organizations have developed safety policies aimed at moving safety to the "driver's seat" to encourage accident prevention. Electrofishing policies vary widely among states and provinces in scope and depth, but all of them have been developed to emphasize safety. An example of a comprehensive policy is the guidance of the U. S. Fish and Wildlife Service (USFWS; Available: https://bit.ly/2UtpAkm). Initiated in the 1980s, the policy now covers safety responsibilities of personnel from administrators to field crew members; training requirements for crew leaders and members; electrical terminology and definitions related to electrofishing; specifications for design and construction of equipment; and safety protocols for operational safety. Agencies and organizations aiming to revise their own policies might consider the USFWS policy as a starting point.

FISH DETERRENCE AND GUIDANCE

Efforts at fish control, not capture, were the first practical applications of electrofishing. Although H. T. Burkey applied for, and received, the first of many U. S. patents for an "electric fish stop" in 1917 (Hartley 1990), actual construction and testing of these AC barriers began in the 1920s. Burkey's use of the term "fish stop" exemplified the issue being addressed on the U. S. West Coast. Each year, countless ditches and canals receiving water from rivers to grow crops on farmlands were diverting large numbers of juvenile salmon (Hallock and Van Woert 1959). State legislatures passed laws requiring that these artificial waterways be screened to prevent fish entry. However, many screens were often installed far inland, assuming that fish would "stop" and return to their original paths; instead, they were being trapped and stranded. Installations were often done as trial-and-error efforts by those unfamiliar with fish behavior. Furthermore, the screens collected debris, requiring expensive maintenance.

Enter F. O. McMillan, an associate professor of electrical engineering at Oregon State College, Corvallis. With funding from the Pacific Power and Light Company and access to facilities and fish (fingerlings of Chinook Salmon *Oncorhynchus tshawytscha*) at the Bonneville Fish Hatchery of the then-Oregon Fish Commission, McMillan set about a rigorous series of experiments. He wanted to elucidate the electric fields generated by electric fish screens and the behavior of fish encountering them. His results, published in the *Bulletin of the United States Bureau of Fisheries* (McMillan 1928), provided insights far in advance of any other work to that point.

McMillan (1928) found that electrified screens should be installed at the mouths of canals and ditches in order to keep fish in a river and encourage their movement downstream. Further, he found that larger fish were more easily deterred by an electric field and it was the juveniles that required special attention. Many fish stops were built with electrodes placed on each side of a ditch. McMillan's use of AC with rows of electrodes arranged as adjacent opposite polarities across ditch entrances was proven much more effective (Figure 3). His findings were applied successfully in redesigns of fish stops (e.g., Tauchi 1931).

Interest in electric barriers and guidance systems increased in the late 1940s, mainly due to the concern for increasing numbers of invasive fishes that threatened native ecosystems. In the 1950s, following the invasion of parasitic Sea Lamprey *Petromyzon marinus* into the upper Great Lakes, AC barriers were used to stop lamprey spawning runs into tributary streams with moderate success. Guidance of other fishes past barriers into traps was achieved with pulsed DC systems (McLain 1957), where the anodes were used to attract fish. Success of these systems was limited by barrier-caused fish kills, floods, and power outages (Applegate et al. 1952; McLain 1957).

Another example of using electrical barriers in attempts to deter invasive fishes began in the Mississippi River in the early 2000s. There, detection of four invasive carps—Grass Carp *Ctenopharyngodon idella*, Bighead Carp *Hypophthalmichthys nobilis,* Silver Carp *H. molitrix,* and Black Carp *Mylopharyngodon piceus*—caused great concern for their potential invasion of the Great Lakes through the Chicago Sanitary and Ship Canal. These carps feed voraciously at the base of the food chain and would undoubtedly alter the Great Lakes ecosystem. Under contract to the U. S. Army Corps of Engineers, Smith-Root built and tested the first electrical barrier at Romeoville, Illinois, in 2002; two more barriers were constructed there in 2006 and 2011. The barriers featured cross-canal rows of substrate-based electrodes (allowing free passage of barge traffic) with a pulsed DC electric

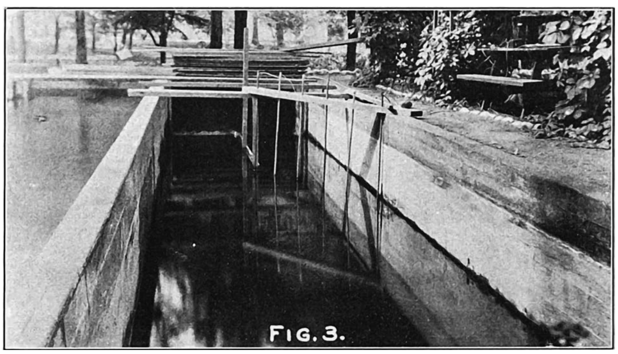


Figure 3. An electric screen tested by F. O. McMillan. Adjacent electrodes have alternating AC polarity (McMillan 1928).

field that increased in intensity in both upstream and downstream directions toward the middle electrode. This "graduated field" diverts fish from further progress by causing them to turn away once they have exceeded their tolerance threshold (Burger et al. 2015). Redundancy is demonstrated not only by the three barriers, but also by the presence of three or four electrical pulsators at each barrier. Thus far, there is no direct evidence (i.e., fish capture) of entry by these carps into Lake Michigan. However, eDNA samples from Lake Michigan tributaries upstream of the barriers have tested positive for Grass Carp and Silver Carp (Available: https://bit.ly/33ZjBqF). For now, the barriers remain operational and are considered essential for a "continuous vigil" against carp invasion.

In general, the story of electric barriers and guidance systems is one of successes mixed with failures. The use of electric barriers in conjunction with other measures such as bubble curtains and sonic beams have also had mixed results. It seems, however, that electric barriers with their modern refinements have been decisive in preventing or reducing the advance of invasive species.

FISH POPULATION ASSESSMENT

In the 1970s, wildlife law enforcement officers in Oklahoma and Texas began observing the illegal use of hand-crank telephones and micro-electronic "pacemakers" by poachers to capture large Flathead Catfish *Pylodictis olivaris.* The Oklahoma Department of Wildlife Conservation's Fisheries Research Laboratory compared the relative efficiencies of confiscated telephones, pacemakers, and a commercial electrofishing control unit for catching Flathead Catfish (Gilliland 1987). These devices all emitted pulsed DC and operated successfully at 10–20 pulses per second (Hz). The catfish would surface at various distances from the boat and would remain on the surface for a few minutes. A "chase" boat was used to capture the surfaced catfish (Figure 4). Why Flathead Catfish (and ictalurids in general) are vulnerable to low-frequency pulsed DC is a mystery yet to be solved.

The story of low-frequency waveforms to capture Flathead Catfish is but one part of the development of various frequencies for fish population assessment. Today, that development has taken a generally uniform path: about 15 Hz for catfish (Gilliland 1987; Miranda and Boxrucker 2009); 30 Hz for salmonids and other cold-water, soft-rayed fishes (Curry et al. 2009; Dunham et al. 2009); 60 Hz for warm-water, spiny-rayed fishes, such as centrarchids (Guy et al. 2009; Pope et al. 2009); and 120 Hz for electroshock-resistant fishes such as cichlids (Thuesen et al. 2011). Despite wide-ranging studies, and some expected variation among choices of frequency, the frequencies used by a diverse community of professionals to capture a variety of fishes are quite consistent, as demonstrated by choices for standardized electrofishing (Bonar et al. 2009).

Figure 4. A stationary electrofishing boat and a chase boat sampling large catfish. Image courtesy of the Oklahoma Department of Wildlife Conservation

In states in the Great Lakes region, the selection of electrofishing frequencies took a different turn. In the 1950s and 1960s, two lampricides (TFM [3-trifluoromethyl-4-nitropheno l] and Bayluscide) were discovered after screening over 6,000 chemicals for efficacy and selectivity. The toxicants are used to kill larval lamprey that burrow into the sediment of streams. In suspected spawning areas, backpack electrofishing is needed to assess the abundance of the larvae before considering the use of toxicants. Dual-frequency electrofishers have been developed to address this need, and are now available commercially (see Electrofishing Equipment Manufacturers).

In the 1950s, Jim McFadden was a graduate student at Pennsylvania State University studying Brook Trout *Salvelinis fontinalis* at Lawrence Creek, Wisconsin. His study was the first to document the selective size bias of electrofishing in a natural setting (McFadden 1961). McFadden caught fish using output from a 2,500-watt, continuous DC generator and fin-clipped them before release. He demonstrated that capture efficiency increased with fish length as fish recruited to the angler fishery.

As biologists recognized the size selectivity of electrofishing, they focused its use on stock assessment to minimize the selective effects on length–age data by excluding smaller fish. Richard Anderson at the University of Missouri–Columbia used electrofishing data to develop a length-based index of adult stock called Proportional Stock Density (PSD) for evaluation of population balance (Anderson 1978). With Largemouth Bass *Micropterus salmoides*, for example, the percent of quality-size fish (≥30 cm TL) in a sample of stock-size fish (≥20 cm TL) should be 40–70% to indicate balance (e.g., Reynolds and Babb 1978). Electrofishing had the advantage of mobility, access to a variety of habitats, and one-at-a-time handling of captured fish to estimate PSD with the smallest sample size (Weithman et al. 1979). Further refinements of the PSD concept, often using electrofishing data, resulted in a family of length-based indices for management (Gabelhouse 1984).

FISH ERADICATION AND ABUNDANCE REDUCTION

In the midst of the Great Depression (circa 1930), Sugarland Industries in Texas faced its own pressing problem. Goslings attracted from a farm adjacent to the company canal were being eaten by Alligator Gar *Atractosteus spatula*; not good for public relations. Colonel J. G. Burr, research director for the Texas Game, Fish, and Oyster Commission, conducted an experiment to eradicate the gar and reduce the number of Common Carp *Cyprinus carpio* in the canal. Colonel Burr floated a 2.4 by 4.8-m barge in the canal and set a 200-volt generator on the deck to provide an AC electrical field in the water. He added a net on the bow that included electrodes and levers to raise and lower the net, plus a headlight to permit nighttime operation. Although not typical of today's equipment, this was likely the first electrofishing boat (Figure 5).

In his report to the American Fisheries Society (Burr 1931), Burr stated that gar were completely eradicated by sinking and "strangulation" (i.e., asphyxiation) and that many carp were collected by netting. His sentiments about the carp were clear

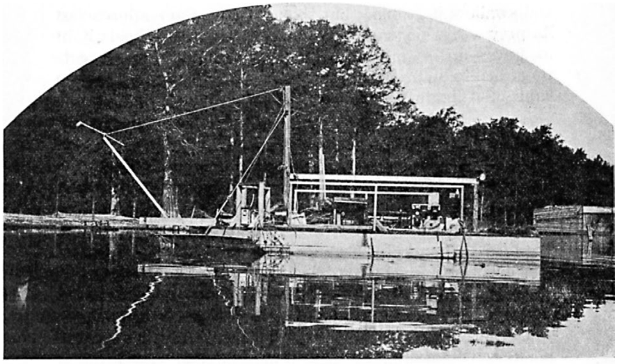


Figure 5. The "Gar Destroyer" built by Colonel J. G. Burr (Burr 1931). Image courtesy of the Louisiana Department of Wildlife and Fisheries

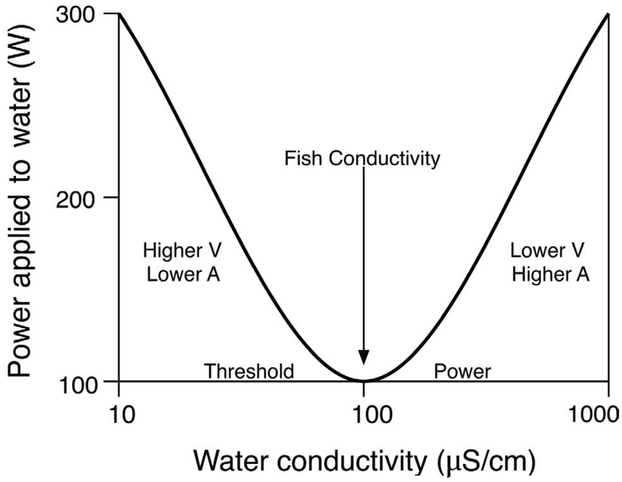


Figure 6. A graph depicting Power Transfer Theory. Threshold power is set arbitrarily at 100 watts. Fish conductivity, the body conductivity that determines efficiency of power transfer, is assumed to be 100 µS/cm. At low conductivities, electrical resistance is high and power is delivered by a combination of high voltage and low current; at high conductivities, the opposite is true. When water conductivity and fish conductivity are equal, maximum power transfers from water to fish; at all other water conductivities, more power must be applied to the water to transfer the same threshold power to fish.

when he said, "The first fish hatchery in Texas was built in Austin in 1880 for the propagation of carp. The hatchery was abolished by the legislature 4 years later, and since that time we have been trying to abolish carp." As proof of gar eradication, he reported that "after the clean-up the goslings were turned out without being molested." However, the electrical method for fish eradication did not immediately catch on.

Fast forward through 7 decades of preferences for fish eradication by piscicides to the 2000s, when eradication by electrofishing gained prominence with a focus on salmonids, especially Brook Trout. In the western United States and western Canada, the Brook Trout is an invasive species that threatens native species, especially Cutthroat Trout *O. clarkii* and Bull Trout *S. confluentus* through hybridization and competition. However, Brook Trout is an iconic native species in the eastern United States and eastern Canada; there, the target of eradication is the competing and hybridizing Rainbow Trout *O. mykiss*. In both regions, eradication by electrofishing has had mixed results. Results of field experiments in both eastern and western regions indicated that removals were most effective in smaller headwater streams. They were expensive in terms of money (Shepard et al. 2014) and effort (Buktenica et al. 2013); at least 3 years of removals by electrofishing were required to achieve some level of success (Kulp and Moore 2000).

Until recently, the legal use of electrofishing has been restricted to professional fisheries biologists. Invasions of large non-native catfishes into rivers of several Mid-Atlantic states has forced management agencies to recruit non-professionals into the ranks of electrofishing personnel. In Virginia, limited numbers of commercial fishers are being granted experimental licenses for the harvest of Blue Catfish *Ictalurus furcatus* with electrofishing. In North Carolina, managers allow recreational use of "hand-crank" electrofishing for the harvest of invasive Blue Catfish and Flathead Catfish. The hand-crank method employs a telephone generator (Fisk et al. 2019) to produce a low-frequency, low-voltage, pulsed DC waveform for effective capture of large fish of these species. (Co-opting the earlier method of poachers for management via recreation seems like *déjà vu*.) Thus far, these unique fisheries appear to have done little to reduce catfish populations (Fisk et al. 2019).

STANDARDIZED FISH SAMPLING

Arguably, the longest-running standardized fish sampling program in North America is the Long-Term Electrofishing program of the Illinois Natural History Survey (McClelland et al. 2012). Initiated in 1957, the program relies on two persons, driver and dip-netter, operating an electrofishing boat using three-phase AC output (mimicking continuous DC) with three standard electrodes off the bow. Fishes are annually collected with a 6.35-mm mesh dip net at 27 fixed stations along the Illinois River during late August to mid-October, when water level is likely to be low but water temperature is ≥14°C. Samples are acceptable for inclusion in the database only if collected when water level is less than a given stage depending on location. These strict standards exemplify the requirements for standardized sampling.

Fisheries biologists seem to have mixed feelings about standardized sampling. Typically, sampling methods have been developed within agencies and organizations to address local conditions and available resources. However, limited budgets and interjurisdictional ecological issues force consideration of data sharing. To enable standardized sampling, the American Fisheries Society published *Standard Methods for Sampling North American Freshwater Fishes* (Bonar et al. 2009). In the book, standard electrofishing equipment is addressed in detail, but standard operations less so, because use of equipment is inherently more variable than the equipment itself. For example, factors for standard equipment include platform (e.g., boat), power source, control unit, electrodes, and dip nets. Standard operations must address choices of electric waveform and other settings, units and levels of effort, crew composition, environmental limits (e.g., day versus night), sampling targets, fish handling, data acquisition, and quality assurance. More work on operational standards is needed if electrofishing standardization is to be truly successful.

Although there are a multitude of choices to make if standardized electrofishing is to be achieved, there have been foundational principles developed to guide these choices; one of these principles is Power Transfer Theory (PTT). In 1980,

A. L. "Larry" Kolz, an electrical engineer at the USFWS Denver Wildlife Research Center, was invited to observe an electrofishing short course offered by the USFWS Fisheries Academy (now the National Conservation Training Center) and to answer any electrical questions. He immediately recognized that success in electrofishing depends upon the transfer of electrical power from water to fish and that water conductivity is a major environmental factor affecting the efficiency of that power transfer (Figure 6). Larry assumed responsibility for co-teaching the USFWS *Principles and Techniques of Electrofishing* course and incorporated the genesis of the PTT, though he didn't publish it for several years (Kolz 1989). At the same time, the theory was tested and proven with fish in the laboratory (Kolz and Reynolds 1989). Later, the Upper Mississippi River Conservation Consortium successfully applied the theory to its sampling program (Burkhardt and Gutreuter 1995). Fourteen years after its publication, Miranda and Dolan (2003) independently verified PTT. Despite initial opposition, PTT is today a paradigm for standardized electrofishing.

FISH WELFARE AND HANDLING

For many decades, it has been understood that electrofishing can injure or kill fish. Hauck (1949) reported internal injuries to Rainbow Trout captured with 60-Hz AC. Pratt (1955) documented mortality rates of Rainbow Trout, Brook Trout, and Brown Trout *Salmo trutta* exposed to both AC and DC. Spencer (1967) reported AC-induced injuries in Largemouth Bass and Bluegill *Lepomis macrochirus*. These studies received little attention or concern at the time because injured fish often appeared normal when released. Also, our profession was focused on harvest and production, not fish welfare. However, the fisheries management community reacted with alarm when Sharber and Carothers (1988) found that half of large (>30 cm TL) Rainbow Trout captured in the Colorado River with 60-Hz pulsed DC had spinal injuries. At an electrofishing conference in 1988, Sharber expressed surprise at the collective reaction to the findings because his study had focused on the effect of various pulse shapes on injury rate. The fact that *all* of the pulse shapes he evaluated caused high injury rates was the key concern for managers. Expressions of legitimate concern followed (Nielsen 1998; Snyder 2003).

Many studies to identify risk factors for harm to fish were conducted during the late 1980s, throughout the 1990s and into the 2000s. These studies generally concluded that electrofishing was more harmful when:

- AC was used instead of DC or pulsed DC (Ainslie et al. 1998);
- pulsed DC was used instead of DC (McMichael 1993; Dalbey et al. 1996);
- higher frequencies of pulsed DC were used for capture (Carline 2001);
- field intensities were set above the minimum needed for capture (McMichael 1993);
- electroshock caused tetany (contracted muscles; Dolan and Miranda 2004);
- fish were repeatedly exposed to electroshock (Clement and Cunjak 2010); and
- when larger fish were shocked versus smaller fish (Clement and Cunjak 2010).

However, two studies found that AC electrofishing caused low injury incidence among salmonids in low conductivities (~10–14 μS/cm) of Appalachian waters (Hudy 1985; Habera et al. 1996). We believe this exception to the injury severity of AC was because the backpack units used produced only 250 continuous watts or less (other makes and models produce nearly twice that), causing the output to be just enough to immobilize fish at very low water conductivity.

Most of the follow-up research of the 1990s–2000s focused on salmonids, a group very susceptible to spinal injury because they have spinal columns with many vertebrae that are small and flexible, and a high fraction of body weight as dorsal muscle that severely contracts during electroshock (Holliman 1999). In retrospect, the focus on salmonids was fortuitous because it provided information about species particularly sensitive to electrofishing. Since then, many agencies have put in place protocols that minimize fish injury while stressing the importance of reliable capture data for management. Electrofishing continues to be a valuable tool for assessment of fish populations when properly used.

Every biologist who ever handled live fish has had to try to hold a wet, slimy, squirming specimen on a measuring board. Various chemical sedatives have been developed and tested, but their use has been restricted if the fish might be caught for human consumption after release (Trushenski et al. 2013). Fish electroimmobilization has been in use for many years. Electroimmobilization is an umbrella term recommended by Reid et al. (2019) to cover electrosedation, electroanesthesia, electrotetany, and electrostunning, all forms of reversible sleep-like states. The concept is simple: subject a fish to a low level of electric current sufficient to cause immobility and loss of sensory perception. Early units delivered 12 volts DC from a car battery during handling operations in a hatchery (Kynard and Lonsdale 1975) or on a boat (Orsi and Short 1987). Portable units were later developed for field work (Hudson et al. 2011; Figure 7) or co-opted from their original purpose (e.g., TENS [Transcutaneous Electrical Nerve Stimulation] units; Weber et al. 2020). The need for a method that allows rapid immobilization and recovery (to replace chemical anesthetics that cause delays and added expense) stimulated research to understand the effects of this treatment on fish. Custom electroimmobilization units that were commercially available are being retired and replaced with backpack units; these are effective for the same purpose and only appropriate electrodes and treatment tanks are needed. Fish can now be anesthetized for various purposes, including surgery that might require many minutes (Reid et al. 2019).

ELECTROFISHING EQUIPMENT MANUFACTURERS

Fish surveys and research projects were advanced through development of functional, safe, and reliable electrofishers. Commercial equipment, made with rugged and reliable electronics, became available in the 1960s as the demand for such equipment increased. Coffelt Electronics produced many types of backpack and boat electrofishers from the 1960s until 2001. The Coffelt units were quite advanced with rectangular DC pulses that could be independently controlled for voltage, frequency, and duty cycle (percent on-time); some produced complex pulse trains. The University of Wisconsin began making electrofishers in about 1967 in partnership with the Wisconsin Department of Natural Resources and the Great Lakes Fishery Commission. One need was to collect larval Sea Lamprey from the substrate, and the solution was a two-channel backpack in which a low frequency was used to stimulate the lamprey up into the water column and a higher frequency to stun them.

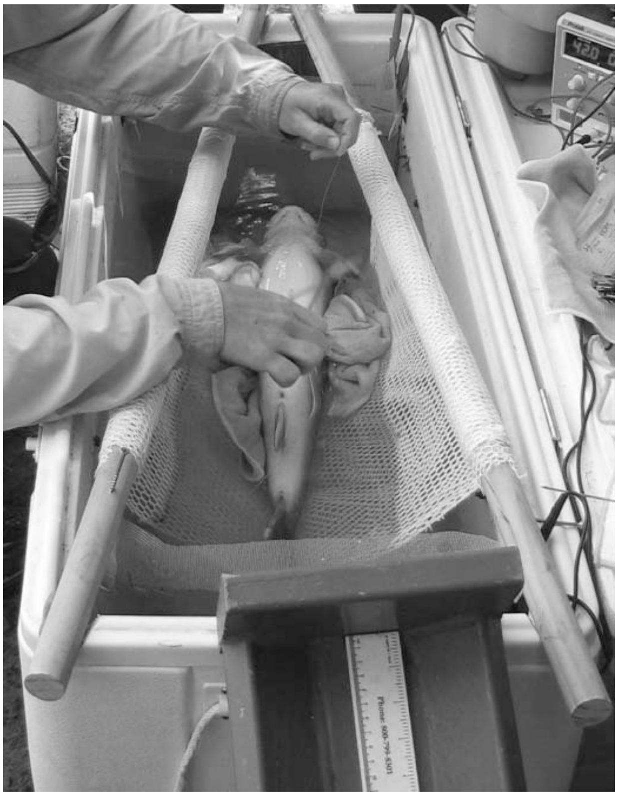


Figure 7. A portable electroimmobilization unit for field work (Hudson et al. 2011).

The University of Wisconsin Engineering Technical Services built backpack and boat electrofishers from 1989 until 2008, when ETS Electrofishing was formed as a private company. Smith-Root was incorporated in 1969 and began making backpack and boat electrofishers. Their line of generator-powered-pulsator boat units produced since the 1980s are powerful, reliable units; some allow fish capture in relatively high conductivity waters. Halltech Aquatic Research of Guelph, Ontario, began making a lower cost backpack electrofisher in 2000 for capturing trout and other stream fishes. Appalachian Aquatics was formed in 2004 to manufacture a simple, inexpensive battery-powered backpack for sampling fishes in low-conductivity Southern Appalachian streams. That basic backpack and more advanced models are now produced by Aqua Shock Solutions. Midwest Lake Management was created in 2003 for management of recreational fishing lakes and ponds. The organization saw the need to develop their own boat electrofisher with independent controls for voltage, frequency, and duty cycle to sample fish for their management business and to help meet the need of fisheries biologists. They began producing their first boat pulsator in 2010 and a backpack unit later. Collectively, these manufacturers have provided a diversity of electrofishers to meet the needs of fisheries management.

Until recently, 5,000 µS/cm was considered about the upper limit for typical boat electrofishing, restricting the method to freshwaters. Hans Grassl, Ltd. in Germany has developed a high amperage unit designed to operate in estuarine waters. As a result of testing in Australia, it has been confirmed that standard size electrofishing boats can operate in waters up to 35,000 µS/cm (Lieschke et al. 2019). This development is a major advance for the expansion of electrofishing into estuarine waters.

CONCLUSION

Since its initial development early in the 20th century, electrofishing has been continually developed and refined to meet management objectives while addressing issues of fish welfare. We have tried to show this pattern of development to address major management objectives. Some developments have not been included due to space limitations for this article. For example, electrical devices are being used to energize fixed areas of shallow waters for fish density estimates (pre-positioned area electrofisher or PAE; Fisher and Brown 1993); to automatically separate soft-shell crayfish from those with hard shells (Chen et al. 1993); and to sedate fish with electrode-equipped gloves during handling (Abrams et al. 2018). Electrofishing is not a “silver bullet” for fish sampling, but is an essential tool for achieving many management objectives. We can expect to see more innovations in electrofishing that will increase its scope and effectiveness in management applications. The American Fisheries Society will continue to be a major source of information for these developments.

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REFERENCES

Abrams, A. E. I., A. M. Ropus, J. L. Brooks, and M. J. Lawrence. 2018. Comparing immobilization, recovery, and stress indicators associated with electric fish handling gloves and a portable electrosedation system. Transactions of the American Fisheries Society 147:390–399.

Ainslie, B. J., J. R. Post, and A. J. Paul. 1998. Effects of pulsed and continuous DC electrofishing on juvenile Rainbow Trout. North American Journal of Fisheries Management 18:905–918.

Anderson, R. O. 1978. New approaches to recreational fishery management of small impoundments. Pages 73–78 *in* G. D. Novinger, and J. G. Dillard, editors. New approaches to the management of small impoundments. American Fisheries Society, North Central Division, Special Publication 5, Bethesda, Maryland.

Applegate, V. C., B. R. Smith, and W. L. Nielsen. 1952. Use of electricity in the control of Sea Lampreys: electromechanical weirs and traps and electrical barriers. U. S. Fish and Wildlife Service Special Scientific Report: Fisheries 92.

Baggs, I. 1863. Improvements in the means of and apparatus for paralysing, capturing or killing fish, birds and other animals. British patent 2644. October 26, 1863.

Bonar, S. A., W. A. Hubert, and D. W. Willis. 2009. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Buktenica, M. W., D. K. Hering, S. Girdner, B. D. Mahoney, and B. D. Rosenlund. 2013. Eradication of nonnative Brook Trout with electrofishing and Antimycin-A and the response of a remnant Bull Trout population. North American Journal of Fisheries Management 33:117–129.

Burger, C. V., J. W. Parkin, M. O'Farrell, and A. Murphy. 2015. Barrier technology helps deter fish at hydro facilities. Hydro Review 34:50–57.

Burkhardt, R. W., and S. Gutreuter. 1995. Improving electrofishing catch consistency by standardizing power. North American Journal of Fisheries Management 15:375–381.

Burr, J. G. 1931. Electricity as a means of garfish and carp control. Transactions of the American Fisheries Society 61:174–182.

Carline, R. F. 2001. Effects of high-frequency pulsed-DC electrofishing on a wild Brown Trout population. North American Journal of Fisheries Management 21:571–579.

Chen, S., K. A. Rusch, and R. F. Malone. 1993. Use of electrical stimulation in the automatic separation of soft-shell crawfish. The Progressive Fish-Culturist 55:114–120.

Clement, M., and R. A. Cunjak. 2010. Physical injuries in juvenile Atlantic Salmon, Slimy Sculpin and Blacknose Dace attributable to electrofishing. North American Journal of Fisheries Management 30:840–850.

Curry, R. A., R. M. Hughes, M. W. McMaster, and D. J. Zafft. 2009. Coldwater fish in rivers. Pages 139–158 *in* S. A. Bonar, W. A. Hubert, and D. W. Willis, editors. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Dalbey, S. R., T. E. McMahon, and W. Fredenberg. 1996. Effect of electrofishing pulse shape and electrofishing-induced spinal injury on long-term growth and survival of wild Rainbow Trout. North American Journal of Fisheries Management 16:560–569.

Dean, J. C., A. J. Temple, and J. W. Smith. 2019. Output performance of U.S.- built backpack electrofishers. North American Journal of Fisheries Management 39:1321–1328.

Dolan, C. R., and L. E. Miranda. 2004. Injury and mortality of warmwater fishes immobilized by electrofishing. North American Journal of Fisheries Management 24:118–127.

Dunham, J. B., A. E. Rosenberger, R. F. Thurow, A. Dolloff, and P. J. Howell. 2009. Coldwater fishes in wadeable streams. Pages 119–138 *in* S. Bonar, W. A. Hubert and D. Willis, editors. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Fisher, W. L., and M. E. Brown. 1993. A prepositioned areal electrofishing apparatus for sampling stream habitats. North American Journal of Fisheries Management 13:807–816.

Fisk, J. M. II, C. W. Morgeson, and M. E. Polera. 2019. Evaluation of recreational hand-crank electrofishing on introduced catfish species in Southeastern North Carolina. North American Journal of Fisheries Management 39:150–165.

Gabelhouse, D. W. Jr. 1984. A length-categorization system to assess fish stocks. North American Journal of Fisheries Management 4:273–285.

Gilliland, E. 1987. Telephone, micro-electronic, and generator-powered electrofishing gear for collecting Flathead Catfish. Proceedings Annual Conference Southeastern Association of Fish and Wildlife Agencies 41:221–229.

Guy, C. S., P. J. Braaten, D. P. Herzog, J. Pitlo, and R. S. Rogers. 2009. Warmwater fish in rivers. Pages 59–84 *in* S. A. Bonar, W. A. Hubert, and D. W. Willis, editors. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Habera, J. W., R. J. Strange, B. D. Carter, and S. E. Moore. 1996. Short-term mortality and injury of Rainbow Trout caused by three-pass AC electrofishing in a southern Appalachian stream. North American Journal of Fisheries Management 16:192–200.

Hager, F. 1934. Die Electrizitat im Dienste der Wildbachfischerei (The use of electricity in the fishing of wild streams). Osterreich Fischereiwirtschaft 7(8):1–3.

Hallock, R. J., and W. F. Van Woert. 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. California Fish and Game 45:227–266.

Hartley, W. G. 1990. The history of electric fishing. Pages 1–3 *in* I. G. Cowx and P. Lamarque, editors. Fishing with electricity: applications in freshwater fisheries management. Fishing News Books, Cambridge, Massachusetts.

Haskell, D. C. 1940. An electrical method of collecting fish. Transactions of the American Fisheries Society 69:210–215.

Haskell, D. C., and W. J. Adelman Jr. 1955. Effect of rapid direct current pulsations on fish. New York Fish and Game Journal 2:95–105.

Haskell, D. C., J. MacDougal, and D. Geduldig. 1954. Reactions and motion of fish in a direct current electric field. New York Fish and Game Journal 1:47–64.

Haskell, D. C., and R. G. Zilliox. 1941. Further developments of the electrical method of collecting fish. Transactions of the American Fisheries Society 70:404–409.

Hauck, F. R. 1949. Some harmful effects of the electric shocker on large Rainbow Trout. Transactions of the American Fisheries Society 77:61–64.

Holliman, F. M. 1999. Assessment and prediction of electroshock-induced injury in North American fishes. Doctoral dissertation, University of Alaska, Fairbanks.

Hudson, J. M., J. R. Johnson, and B. Kynard. 2011. A portable electronarcosis system for anesthetizing salmonids and other fish. North American Journal of Fisheries Management 31:335–339.

Hudy, M. 1985. Rainbow Trout and Brook Trout mortality from high voltage AC electrofishing in a controlled environment. North American Journal of Fisheries Management 5:475–479.

Kolz, A. L. 1989. A power transfer theory for electrofishing. U.S. Fish and Wildlife Service Technical Report 22:1–11.

Kolz, A. L., and J. B. Reynolds. 1989. Determination of power threshold response curves. U.S. Fish and Wildlife Service Technical Report 22:15–24.

Kulp, M. A., and S. E. Moore. 2000. Multiple electrofishing removals for eliminating Rainbow Trout in a small Southern Appalachian stream. North American Journal of Fisheries Management 20:259–266.

Kynard, B., and E. Lonsdale. 1975. Experimental study of galvanonarcosis for Rainbow Trout (*Salmo gairdneri*) immobilization. Journal of the Fisheries Research Board of Canada 32:300–302.

Larimore, R. W., L. Durham, and G. W. Bennett. 1950. A modification of the electric fish shocker for lake work. The Journal of Wildlife Management 14:320–323.

Lieschke, J. A., J. C. Dean, and A. Pickworth. 2019. Extending the effectiveness of electrofishing to estuarine habitats: Laboratory and field assessments. Transactions of the American Fisheries Society 148:584–591.

Martinez, P. J., and A. L. Kolz. 2013. Performance of four boat electrofishers with measured electrode resistances for electrofishing boats and rafts. North American Journal of Fisheries Management 33:32–43.

McClelland, M. A., G. G. Sass, T. R. Cook, K. S. Irons, N. N. Michaels, T. M. O'Hara, and C. S. Smith. 2012. The long-term Illinois River fish population monitoring program. Fisheries 37:340–350.

McFadden, J. T. 1961. A population study of the Brook Trout, *Salvelinus fontinalis*. Wildlife Monographs 7:3–73.

McLain, A. L. 1957. The control of the upstream movement of fish with pulsated direct current. Transactions of the American Fisheries Society 86:269–284.

McMichael, G. A. 1993. Examination of electrofishing injury and short-term mortality in hatchery Rainbow Trout. North American Journal of Fisheries Management 13:229–233.

McMillan, F. O. 1928. Electric fish screen. Bulletin of the United States Bureau of Fisheries 44:97–128.

Miranda, L. E., and J. Boxrucker. 2009. Warmwater fish in large standing waters. Pages 29–42 *in* S. A. Bonar, W. A. Hubert, and D. W. Willis, editors. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Miranda, L. E., and C. R. Dolan. 2003. Test of a power transfer model for standardized electrofishing. Transactions of the American Fisheries Society 132:1179–1185.

Miranda, L. E., and A. B. Spencer. 2005. Understanding the output of a Smith-Root GPP electrofisher. North American Journal of Fisheries Management 25:848–852.

Nielsen, J. L. 1998. Scientific sampling effects: electrofishing California's endangered fish populations. Fisheries 23(12):6–12.

Novotny, D. W., and G. R. Priegel. 1971. A guideline for portable direct current electrofishing systems. Wisconsin Department of Natural Resources Technical Bulletin 51

Novotny, D. W., and G. R. Piegel. 1974. Electrofishing boats: improved designs and operational guidelines to increase the effectiveness of boom shockers. Wisconsin Department of Natural Resources Technical Bulletin 73.

Orsi, J. A., and J. W. Short. 1987. Modifications in electrical anesthesia for salmonids. Progressive Fish-Culturist 49:144–146.

Pope, K. L., R. M. Neumann, and S. D. Bryan. 2009. Warmwater fish in small standing waters. Pages 13–27 *in* S. A. Bonar, W. A. Hubert and D. W. Willis, editors. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Pratt, V. S. 1955. Fish mortality caused by electrical shockers. Transactions of the American Fisheries Society 84:93–96.

Rayner, H. J. 1949. Direct current as an aid to the fishery worker. Progressive Fish-Culturist 11:169–170.

Reid, C. H., C. S. Vandergoot, J. D. Midwood, E. D. Stevens, J. Bowker, and S. J. Cooke. 2019. On the electroimmobilization of fishes for research and practice: opportunities, challenges and research needs. Fisheries 44:576–585.

Reynolds, J. B., and L. R. Babb. 1978. Structure and dynamics of Largemouth Bass populations. Pages 50–61 *in* G. D. Novinger, and J. G. Dillard, editors. New approaches to the management of small impoundments. American Fisheries Society, North Central Division, Special Publication 5, Bethesda, Maryland.

Sharber, N. G., and S. W. Carothers. 1988. Influence of electrofishing pulse shape on spinal injuries in adult Rainbow Trout. North American Journal of Fisheries Management 8:117–122.

Shepard, B. B., L. M. Nelson, M. L. Taper, and A. V. Zale. 2014. Factors influencing successful eradication of nonnative Brook Trout from four small Rocky Mountain streams using electrofishing. North American Journal of Fisheries Management 34:988–997.

Shetter, D. S. 1938. The use of electricity in the fishing of wild streams (Review). The Progressive Fish-Culturist 5:32–33.

Shetter, D. S. 1948. The electric shocker and its use in Michigan streams. The Progressive Fish-Culturist 10:43–47.

Smolian, K. 1944. Die Electrofischerei. Sammlung fischereilicher Herausgegeben vom Relchsverband der Deutschen Fischerei, Heft 35 (Electrofishing. Collection of fisheries published by the Relchsverband der Deutschen Fischerei, Issue 35). Verlag J. Neumann, Neudamm und Berlin.

Snyder, D. E. 2003. Electrofishing and its harmful effects on fish. U.S. Geological Survey, Biological Resources Division, Information and Technology Report USGS/BRD/ITR-2003-0002, Reston, Virginia. U.S. Government Printing Office, Denver.

Spencer, S. L. 1967. Internal injuries of Largemouth Bass and Bluegills caused by electricity. Progressive Fish Culturist 29:168–169.

Tauchi, M. 1931. On the electric fish screen. Japanese Journal of Limnology 1:22–24.

Thuesen, P. A., D. J. Russell, F. E. Thomson, M. G. Pearce, T. D. Vallance, and A. E. Hogan. 2011. An evaluation of electrofishing as a control measure for an invasive tilapia (*Oreochromis mossambicus*) population in northern Australia. Marine and Freshwater Research 62:110–118.

Trushenski, J. T., J. D. Bowker, S. J. Cooke, D. Erdahl, T. Bell, J. R. MacMillan, R. P. Yanong, J. E. Hill, M. C. Fabrizio, and J. E. Garvey. 2013. Issues regarding the use of sedatives in fisheries and the need for immediate-release options. Transactions of the American Fisheries Society 142:156–170.

Weber, M. J., R. E. Weber, and E. E. Ball. 2020. Using radiotelemetry to evaluate poststocking survival and behavior of large fingerling Walleye in three Iowa, USA, lakes. North American Journal of Fisheries Management 40:48–60.

Weithman, A. S., J. B. Reynolds, and D. E. Simpson. 1979. Assessment of structure of Largemouth Bass stocks by sequential sampling. Proceedings Annual Conference Southeastern Association of Fish and Wildlife Agencies 33:415–424. AFS