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Invited overview: conclusions from a review of electrofishing and its harmful effects on fish

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Contents

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Abstract

These conclusions are extracted from a published review and synthesis of literature on electrofishing and its harmful effects on fish. Although a valuable sampling technique for over half a century, electrofishing, which involves a very dynamic and complex mix of physics, physiology, and behavior, remains poorly understood. New hypotheses have been advanced regarding "power transfer" to fish and the epileptic nature of their responses to electric fields, but these too need to be more fully explored and validated. Fishery researchers and managers are particularly concerned about the harmful effects of electrofishing on fish, especially endangered species. Although often not externally obvious or fatal, spinal injuries and associated hemorrhages sometimes have been documented in over 50% of fish examined internally. Such injuries can occur anywhere in the electrofishing field at or above the intensity threshold for the twitch response. These injuries are believed to result from powerful convulsions of body musculature (possibly epileptic seizures) caused mostly by sudden changes in voltage as when electricity is pulsed or switched on or off. Significantly fewer spinal injuries are reported when direct current, low-frequency pulsed direct current ($\leq$ 30 Hz), or specially designed pulse trains are used. Salmoninae are especially susceptible. Other harmful effects, such as bleeding at gills or vent and excessive physiological stress, are also of concern. Mortality, usually by asphyxiation, is a common result of excessive exposure to tetanizing intensities near electrodes or poor handling of captured specimens. Reported effects on reproduction are contradictory, but electrofishing over spawning grounds can harm embryos. Electrofishing is often considered the most effective and benign technique for capturing moderate to large-size fish, but when adverse effects are problematic and cannot be sufficiently reduced, its use should be severely restricted.

Preface

This invited overview is a modified extraction of the conclusions, summary of factors affecting electrofishing injury and mortality, abstract, and selected illustrations from Snyder (2003), an extensive review and synthesis of literature published prior to year 2000 on "Electrofishing and Its Harmful Effects on Fish." For most supporting details and references, please refer to the full report. Online copies of the report in Adobe Portable Document Format (PDF) can be viewed or downloaded from the USGS-BRD publications website at <http://www.fort.usgs.gov/products/Publications/21226/21226.asp>. Printed copies are available from: U.S. Bureau of Reclamation, Upper Colorado Regional Office, Attn: Tonita Loveday, 125 South State Street, Salt Lake City, Utah 84138, USA.

Electrical fields and responses of fish

Electrofishing, the use of electric fields in water to capture or control fish, has been a valuable sampling technique for over half a century, but it involves a very dynamic, complex, and poorly understood mix of physics, physiology, and behavior. To be effective, the electric field in the water must be sufficiently strong at appropriate distances from the electrodes to elicit the desired responses by targeted fish. The size, shape, and nature of that field are defined by the distribution and pattern of electrical intensity which is determined by the peak electrical potential (voltage differential), type of current, and waveform generated between and around the electrodes; the position, size, and shape of those electrodes; the conductivity of the water and bounding and surrounded media; and the size and dimensions of the water body.

What we know or believe about the responses of fish to electric fields is the cumulative result of many years of individual and often piece-meal research. However, in a much more concerted effort, many of these responses were intensively investigated and others revealed in the 1960s at the Biarritz Hydrobiological Station in France (Blancheteau et al., 1961; Lamarque, 1963, 1967, 1990; Vibert, 1963, 1967; Blancheteau, 1967). Unfortunately, many questions remained and the interpretation of some results was either difficult to understand or questionable. In a more recent attempt to better understand and explain the inter-

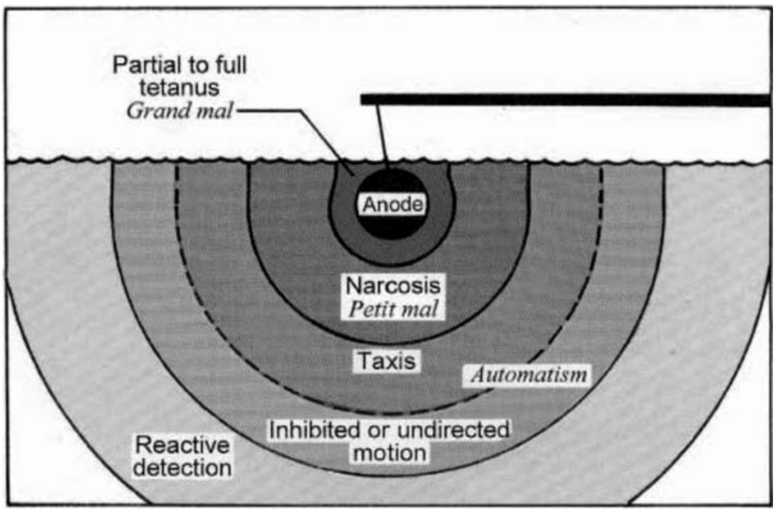

Figure 1. Major intensity-dependent electrofishing response zones. The outer boundaries of response zones for a spherical anode at the surface and sufficiently distant from the cathode are more-or-less hemispherical shells around the anode that represent field-intensity thresholds for the associated responses. Actual and relative sizes of the zones are specimen dependent (species, size, condition, and orientation) and vary with electrical output, electrode size and shape, and environmental conditions. Labels in italics represent corresponding phases of epilepsy as suggested by Sharber and Black (1999) except that here the phase of tonic–clonic contractions (quivering or pseudo-forced swimming) between petit mal and grand mal (narcosis and tetany) is treated as the initial part of grand mal (partial tetany). Zone of reactive detection is sometimes referred to as zone of perception. Zones of taxis, narcosis, and tetany represent the effective range for fish capture using direct and pulsed direct currents. (Reproduced from Snyder (2003), Figure 11.)

action between fish and electric fields, electrofishing has been treated as a power-related phenomena. According to this "power-transfer theory for electrofishing," the relationship between electrical power in the water and in the fish is a function of the ratio of water conductivity to the effective conductivity of the fish (Kolz and Reynolds, 1989; Kolz et al., 1998). Even more recently, it has been suggested that the observed responses of fishes to an electric field, including twitches (in the zone of perception or reactive detection), taxis, narcosis, and tetany, are essentially aspects of the same phases of epilepsy (automatism, petit mal, and grand mal) that are observed in humans and other animals subjected to electroconvulsive therapy (Sharber et al., 1994, 1995; Sharber and Black, 1999) (Figure 1). Most of the currently accepted or proposed concepts for explaining or better understanding the responses of fish to electric fields, and the mechanisms involved, need to be further explored, validated, refined, and integrated to advance the science and technology of electrofishing. This might be accomplished best through a well-coordinated, cooperative, interdisciplinary program for future electrofishing research.

Harmful effects

Stress, injuries, and sometimes mortalities among captured fish are unavoidable consequences of electrofishing and most other collection techniques. Among the more effective gear and techniques available for collecting fish, biologists usually select those known to be least harmful, but comparative data on harmful effects are often lacking or inconclusive.

In many cases, especially prior to the late 1980s, electrofishing had been considered not only the most effective but also the least harmful means to capture fish, particularly moderate to large-size specimens. Despite occasional reports of substantial harm to fish, the relatively benign nature of electrofishing had been assumed because generally fish recovered quickly and few mortalities or external injuries were observed or reported. Also, the most frequently noted external effects, brands, were often dismissed by experienced electrofishers as harmless, temporary effects rather than as indicators of potentially serious spinal injuries or hemorrhages. But since the late 1980s, many investigators have shown that assessment of electrofishing injuries based only on externally obvious criteria can be highly inadequate.

Sharber and Carothers (1988) X-rayed and necropsied many large rainbow trout captured by electrofishing, found spinal injuries and associated hemorrhages in 44–67% of the fish, and concluded that without such analysis, most of these injuries would go undetected unless they were very severe. Especially severe spinal injuries or muscular hemorrhages (Figures 2 and 3) can be represented

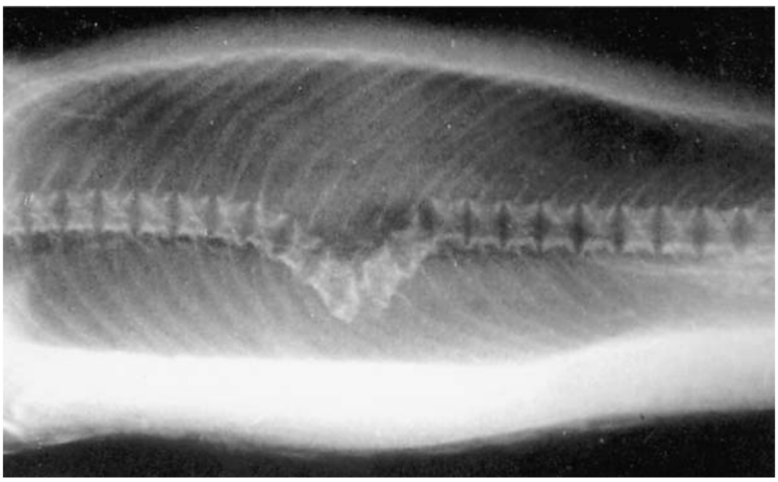

Figure 2. Dorsal-view X-ray of a rainbow trout (*Oncorhynchus mykiss*) revealing severe spinal misalignment and fractured vertebrae caused by electrofishing. (Photograph provided by and used with permission of N. G. Sharber, Flagstaff, Arizona; reproduced from Snyder (2003), Figure 16-top.)

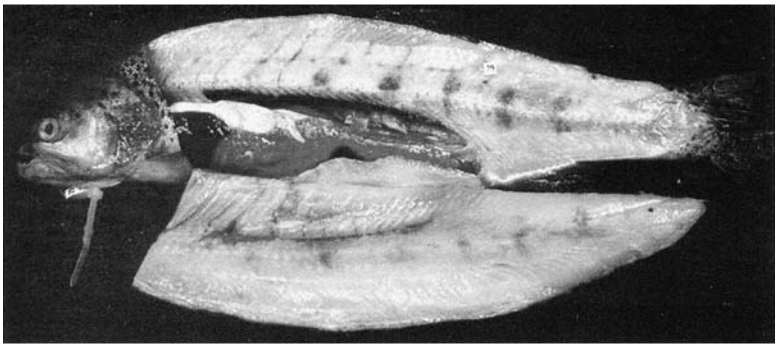

Figure 3. Necropsy fillet of rainbow trout (*Oncorhynchus mykiss*) revealing multiple hemorrhages and associated tissue and vertebral damage caused by electrofishing. (Photograph provided by and used with permission of N. G. Sharber, Flagstaff, Arizona; reproduced from Snyder (2003), Figure 17-top.)

externally by brands (particularly those that are in fact bruises, Figure 4), bent backs, punctures, or abnormal swimming, but in most fish even severe injuries are not externally obvious. When electrofished specimens were similarly examined in subsequent investigations by other biologists (e.g., Holmes et al., 1990; Meyer and Miller, 1991; Fredenberg, 1992; Newman, 1992; McMichael, 1993; Hollender and Carline, 1994), they too documented large percentages of fish with electrofishing injuries for some species, especially salmonids. As a result, new research focused on the extent of such injuries in specific applications, longer-term impacts, causes, and modifications to gear and techniques that might reduce harmful effects. Based on these studies, some programs, agencies, and institutions have been re-evaluating their use of electrofishing and instituting policies or guidelines to reduce the potential for injury. But we must better understand the problem, the factors involved, and how to minimize injuries.

Factors affecting injuries and mortality

Factors considered in the literature to affect electrofishing injuries and mortalities include type of current, field intensity, duration of exposure, orientation of fish relative to lines (net direction) of current, and for alternating current (AC) and pulsed direct current (PDC), waveform characteristics such as shape, wave or pulse frequency, and pulse width. Additional factors considered were fish species, size, and condition. However, data

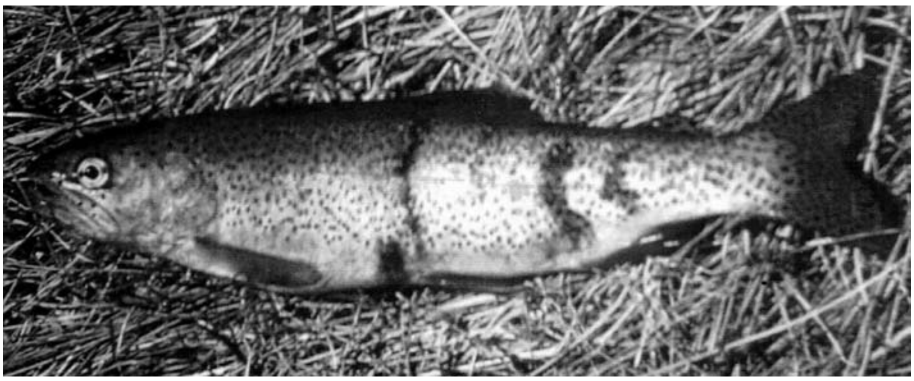

Figure 4. Brands (bruises or dark pigmental discolorations) in rainbow trout (*Oncorhynchus mykiss*) caused by electrofishing. Brands are usually temporary external manifestations of spinal injury, but injured fish often lack brands. (Photograph provided by and used with permission of W. A. Fredenberg, Creston National Fish Hatchery, Kalispell, Montana; reproduced from Snyder (2003), Figure 2.)

regarding the effects of these factors are sometimes sparse, difficult to compare, and often questionable.

Available data generally support the contention that of the three types of electrofishing currents, AC is most harmful, DC (constant direct current) least, and PDC usually somewhere between depending on the frequency and complexity of pulses. Although there are reports of no mortality or injury for each type of current, when such adverse effects do occur and comparisons are possible, AC tends to be more lethal than either DC or PDC, and AC and moderate to high-frequency PDCs tend to cause more spinal injuries and hemorrhages than DC, low-frequency PDCs, or the only complex PDC tested to date—Complex Pulse System (CPS, a patented pulse train of 3 square pulses at 240 Hz delivered 15 times per second). The extent of mortality or injury caused by each of these currents varies considerably with how they are used, other electrical parameters, biological factors, and environmental conditions. With enough field intensity and duration of exposure, any type of current can be lethal, and under certain conditions even DC can injure substantial numbers of fish.

As for most chemical substances and physical parameters affecting living organisms, concentration (in this case, field intensity) and duration of exposure are the primary factors affecting physiological stress and mortality in fish subjected to electrofishing currents. Beyond lethal threshold levels, increases in electrical-field intensity or duration of exposure typically result in increased mortality. However, it is not field intensity itself, but the magnitude of voltage differential generated across fish (usually head-to-tail voltage) or specific nerves or tissues that causes electrofishing mortalities and most sublethal physiological effects and behavioral responses. Voltage differential is a function of both field intensity and orientation of the fish relative to the lines of current.

Unlike its crucial effect on electrofishing mortality, field intensity beyond requisite threshold levels has an unclear, but evidently not critical effect on electrofishing injuries. Spinal injuries and associated hemorrhages can occur in fish located anywhere in the field at or above the intensity threshold for twitch in the zone of perception. In the zone of perception, as many fish, including those injured by the electrical field, are likely to

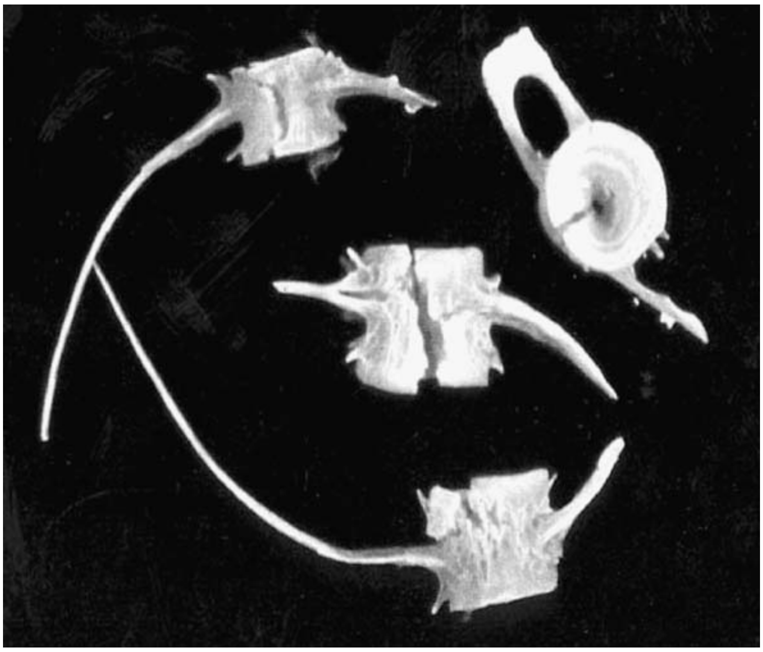

Figure 5. Fractured vertebrae from a rainbow trout (*Oncorhynchus mykiss*) caused by electrofishing. (Photograph provided by and used with permission of W. A. Fredenberg, Creston National Fish Hatchery, Kalispell, Montana; reproduced from Snyder (2003), Figure 18.)

escape the field as move into the effective zones of the field for capture (taxis, narcosis, and tetany).

The principal cause of spinal injuries appears to be muscular convulsions (myoclonic jerks or seizures) induced by sudden changes in field intensity or, more specifically, in voltage differential across the fish or affected tissues at or above a relatively low threshold in magnitude of change for twitch. Such sudden changes occur when current is switched on and off or pulsed, when fish leap frantically out of and back into the electrified water, and when netted fish are removed from or dipped in and out of the field. Accordingly, duration of exposure in DC should have no effect on incidences of spinal injuries while fish remain in the water, but in PDC, longer exposures subject fish to more pulses and thereby increase potential for spinal injury. However, neither muscular convulsions as the principal cause of spinal injuries in fish nor sudden changes in voltage differential as the principal cause of the convulsions have been experimentally documented. Also, the latter is contradicted, seemingly, by the observation of twitches during uninterrupted DC and occasional documentation of as many spinal injuries (at least minor ones) in DC with just two sudden change events (when the current is switched on and later off) as in some simple or complex PDCs with numerous sudden changes in voltage differential.

Increases in spinal injuries with exposure time might be expected as well for AC with its cyclic changes in voltage differential and direction (effectively alternating half-sine pulses), but limited experimental evidence suggests otherwise. Perhaps the changes in AC voltage are not sufficiently sudden (if so, the same would apply to half-sine PDC), or the change in direction precludes possible consecutive-pulse summation effects that might sometimes be necessary to achieve the threshold magnitude of change in voltage differential.

Whether the probability or degree of spinal injuries and hemorrhages increases with field intensity or not, fish in a state of narcosis (petit mal) or tetany (grand mal) may no longer be subject to the sudden convulsions that are believed to cause most spinal injuries in PDC (and possibly AC). Injuries might still occur during transition between these states and when fish are removed from the field. If some spinal injuries do occur during tetany, as has long been suspected but unproven, the sustained muscular tension would have to be sufficiently strong to permanently compress one or more portions of the spinal column, burst blood vessels, and possibly fracture vertebrae (Figure 5). Aside from this possibility, measures to specifically reduce the intense zone of tetany around an electrode might not have much impact on the frequency of spinal injuries, but they should reduce incidences of severe stress, fatigue, and mortality.

Orientation of fish when first exposed to the effective portion of the field is probably as significant a factor in electrofishing injuries as in other responses and mortality. However, based on limited evidence, greatest effect appears to occur when fish are perpendicular to rather than parallel to the lines of current (minimum rather than maximum head-to-tail voltage differential). If so, experiments to assess the injurious effects of electric currents on fish might be confounded or biased to minimum effects if fish are held parallel to the direction of current.

For PDC, pulse frequency appears to be a primary factor affecting the incidence of spinal injuries and may be a significant secondary factor in electrofishing mortalities. As expected if spinal injuries are caused primarily by sudden changes in electrical potential, the incidence of injuries is generally lowest for low-frequency currents and increases with pulse frequency. With regard to incidences of spinal injuries, the CPS pulse train with a primary frequency of 15 Hz appears comparable to simple low-frequency currents (and DC). It is unknown whether other pulse trains or complex variations of PDC also result in as few injuries as low-frequency PDCs.

The effects of pulse shape or waveform, pulse width or duty cycle, and voltage spikes on mortality and spinal injuries have been inadequately investigated and data that are available are difficult to compare and sometimes contradictory. Although exponential and half-sine PDCs have been implicated as particularly lethal and half-sine, quarter-sine, and square PDCs as particularly injurious, the effects of PDC waveforms on electrofishing mortality and injury remain inconclusive. Likewise for AC waveforms, despite one comparison of sine-wave and triangular-wave AC which revealed no significant differences in incidence of externally obvious injuries but notable differences in the nature and perhaps severity of those injuries. The little data that exists with regard to pulse duration or duty cycle suggests no effect on mortality and a tendency for fewer spinal injuries using currents with longer pulses or greater duty cycles. A limited-scope investigation suggested that voltage spikes have little or no impact on electrofishing injuries or mortality.

Evidence to date strongly indicates that trout, char, and salmon (subfamily Salmoninae) are more susceptible to spinal injuries, associated hemorrhages, and probably mortality during electrofishing than most other fishes. Among other species, burbot (*Lota lota*) and sculpins (Cottidae) were reported to be particularly susceptible to electrofishing mortality, at least under some environmental and electrical-field conditions, whereas goldeye (*Hiodon alosoides*), some suckers (Catostomidae), channel catfish (*Ictalurus punctatus*), largemouth bass (*Micropterus salmoides*), walleye (*Stizostedion vitreum*), and possibly paddlefish (*Polyodon spathula*) were reported to be more susceptible to electrofishing-induced spinal injuries and associated hemorrhages. Electrofished mountain whitefish (*Prosopium williamsoni*) have been reported to be particularly susceptible to bleeding of the gills.

Because voltage differential across fish or specific tissues increases with size, larger fish have been expected to be more susceptible to electrofishing mortality and injury than smaller fish. However, laboratory and field data suggest that increases in electrofishing mortality with size might only occur with increases in exposure time and some researchers have reported greater electrofishing mortality among smaller fish. Some data support an increased frequency of spinal injuries as fish size increases, but other data do not, and so the importance of size remains questionable.

The physical condition of fish can affect their susceptibility to electrofishing injury and mortality, but assessment of this factor is based mostly on suppositions and casual observations rather than specific experiments and data. Fish in poor health may respond less strongly to electric fields, thereby reducing chances for spinal injury, but they also may be less able to withstand the stresses of tetany and apnea during narcosis, thereby increasing probability of death. On the other hand, weakened skeletal systems probably make fish especially susceptible to spinal injuries. Temperate fishes electrofished during late fall through early spring may be less likely to suffer either spinal injuries or mortality due to lower water temperatures that substantially reduce metabolism and slow responses.

If there are significant harmful impacts on fish resulting from single electrofishing events, the effects of multiple events should be cumulative. In at least some cases, the stress of repeated handling has greater impact on delayed mortality than repeated exposures to electric fields. The incidence of total injuries among captured fishes inhabiting repeatedly sampled waters increases cumulatively, not only during multiple-pass sessions, but in successive seasons or years of sampling. Some newly captured fish may have been injured during prior treatments or sampling but at that time either escaped the effective portion of the electric field or were missed by netters.

Impacts on reproduction, embryos, and larvae

Electrofishing can also affect reproduction and early life stages. In addition to or as a result of injuries, exposure of ripe fish to electrofishing fields can cause significant damage to, or premature expulsion of, gametes and sometimes reduces viability of subsequently fertilized eggs. Electrofishing over active spawning grounds can also significantly affect survival of embryos on or in the substrate if exposed during their more sensitive stages (prior to acquisition of eye pigment). Exposure of recently hatched larvae might not cause significant mortality but can reduce growth rates for at least a few weeks. Field intensity and duration of exposure appear to be the most critical electrical factors affecting embryos and larvae.

Summary – Recommendations

Although verification through targeted research is still needed, the immediate cause of most spinal injuries and related hemorrhages appears to be strong myoclonic jerks (perhaps epileptic seizures referred to as automatisms) elicited by sudden changes in electrical potential. As might be expected if this is true, comparative investigations generally have revealed that DC causes the fewest spinal injuries and hemorrhages and that low-frequency PDCs (≥30 Hz, the lower the better) and at least one complex PDC, CPS, cause substantially fewer spinal injuries and hemorrhages than higher-frequency PDCs and AC. Accordingly, and if they can be used effectively, such currents are recommended to minimize potential injuries. Unfortunately, when used to generate fields of similar intensity, very low-frequency PDCs (e.g., 15 Hz, CPS) are generally less effective for capturing fish than higher-frequency PDCs, perhaps because they, like DC, generally have higher field-intensity thresholds for the desired responses. If the equipment and conductivity of the water allow, more power (field intensity) is usually needed to use these currents effectively. But regardless of the current used, care must be taken to use no more power than is necessary for effective capture. Although high-intensity portions of the electrical field, especially in the zone of tetany, might not have any significant impact on the incidence or severity of spinal injuries, they substantially increase the potential for severe stress and mortality due to excessive fatigue and asphyxiation. In addition to limiting power output, use of the largest practical electrodes for water conditions and power output will minimize the size of the most intense portions of the field, particularly the zone of tetany around the electrodes. Efforts to reduce electrical field exposure and handling time, avoid dipping netted fish back into the electrical field, and improve holding tank conditions should also reduce the potential for severe stress, injury, and mortality. When possible and not critical to the sampling program, electrofishing over active spawning grounds should be avoided.

Electrofishing is a valuable tool for fishery management and research, but when resultant injuries to fish, or other adverse effects, are a significant problem and cannot be adequately reduced by changes in procedure, gear, and technique, we must abandon or severely limit its use and seek less harmful alternatives. This is our ethical responsibility to the fish, the populace we serve, and ourselves.

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