IMPACTS OF ELECTROFISHING ON FISH

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A request for information on effects of electrofishing was published in *Fisheries* by the American Fisheries Society and printed in various other fishery newsletters and bulletins. A survey of electrofishing experiences, observations, and recommendations was also distributed to Colorado River Basin Researchers and fishery faculty and graduate students at Colorado State University. In response, many researchers provided copies of unpublished manuscripts and reports and conveyed their experiences, observations, and concerns. The more pertinent of this unpublished information is included, with permission, in this review.

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SUMMARY

Electrofishing, a valuable sampling technique in North America for four decades, is in a state of flux. The field is expanding with new equipment, applications, and understanding but contracting with increased concern for comparability of data and safety of operators and fish. Researchers and managers in the Colorado River Basin are especially concerned about potential adverse effects on endangered fishes. This report is a review of literature and available unpublished information on the effects of electric fields on fish. It includes recommendations for interim policy and research to determine if, how, and to what extent electrofishing adversely impacts the species of concern and means for minimizing those impacts.

Recent investigations in several states have documented substantial injury to the spines of fish using modern electrofishing equipment with pulsed direct current. The injuries result from powerful convulsions of body musculature (epileptic seizures according to one authority) and include fractured vertebrae; spinal compressions, breaks, and misalignments; and associated hemorrhages and damage to muscles, nerves, and other tissues. The problem is real, wide-spread, and not simply a matter of too much power or close proximity to the anode. Spinal injuries have been observed in fish netted outside the high-intensity zone of tetany and might occur at electric-field intensities below the threshold for taxis. The injuries are often not externally obvious or fatal. Most spinal injuries can only be detected by X rays or necropsy. When external signs such as brands or bent backs are present, serious injuries are indicated. Unless the injury is severe, most fish experiencing spinal injuries heal, survive, and appear to behave normally. Accordingly, concern by some biologists is shifting from effects on individuals to effects on populations.

The specific electrical, environmental, and biological factors associated with spinal injuries remain uncertain, in part because, the results of pertinent investigations are often inconsistent or contradictory. However, sudden changes in voltage differential, as when current is switched on or off, appear to be the most likely cause. Use of low-frequency pulsed direct current (30 Hz), specially designed pulse trains, or continuous direct current effectively reduces the incidence of spinal injuries, but does not eliminate the problem. The severity of the problem varies widely with equipment, technique, environment, species, and probably size and condition of the fish. Reported incidences of spinal injury range from none detected to over 90%. Among the few species studied thus far, the Salmoninae (trout, char, and salmon) are by far the most susceptible species. Endangered Colorado River Basin fishes are not immune, but neither they nor close relatives have yet been studied to determine whether spinal injuries are a significant problem.

Other harmful effects of electrofishing are also of concern. Mortality, usually by asphyxiation, is a common result of excess exposure to tetanizing currents near the anode or poor handling of captured specimens. Tetany can be minimized by prudent selection of electrical parameters such as power output and electrode size. Bleeding at the gills or vent might not be associated with either spinal injuries or the stresses of tetany. Effects of electrofishing on the reproductive behavior of near ripe or spawning fish remain unknown, but there is evidence that electrofishing over spawning grounds might harm developing embryos. Adverse effects of electric fields on fish larvae have not been investigated.

Until proven otherwise, it is recommended that Colorado River Basin researchers assume that presently used and available electrofishing techniques can cause significant injury to endangered or other native fishes. Alternatives to electrofishing should be considered in ongoing programs and use of electrofishing in new programs should be minimized or delayed until the necessary research on electrofishing impacts is completed and definitive policy can be established. If electrofishing remains the only reasonable capture technique for data critical to endangered species recovery, then electrofishing equipment and procedures should be continuously monitored and adjusted to assure least harm to the fish.

Many biologists across North America now acknowledge that spinal injuries may be a serious consequence of electrofishing, at least for some species. It is time for a concerted, well-funded, national or international effort to document the factors, thresholds, and mechanisms involved and determine means for minimizing injury while maintaining adequate capture efficiency. Where electrofishing injury is a problem and cannot be adequately reduced, the technique must be abandoned or severely limited. As fishery biologists, this is our ethical responsibility to the fish, the populace we serve, and ourselves.

INTRODUCTION

Electrofishing, the use of electric fields in water to capture or control fish, has been a valuable sampling technique in North America for four decades, but it is now in a state of flux. The use of electrofishing is expanding with new equipment and applications, but it is also being limited by increasing concerns for comparability of data, operator safety, and injury to fish.

The present concern over electrofishing injuries was sparked by Sharber and Carothers' 1988 publication which documented substantial and unexpected injury to the spine and associated tissues of 44 to 67% of the rainbow trout (*Oncorhynchus mykiss*, >300 mm TL, total length) electrofished with modern equipment and pulsed direct current (PDC). Most of the injuries were detected only by X-ray analysis or necropsy in fish that otherwise appeared quite normal (Figure 1). Such spinal injuries have long been associated with use of alternating current (AC), but until now, had been largely overlooked as a significant problem with most forms of PDC. This situation persisted despite much earlier publications documenting high incidence of injury with PDC. For example, Horak and Klein (1967) observed indications of probable spinal injury in 39% of the hatchery-reared rainbow trout they electrofished with 60-Hz PDC.

The renewed concern about potential electrofishing injury has prompted biologists and managers in several agencies to investigate the existence and extent of the problem in their own situations. Reports by Holmes et al. (1990), McMichael et al. (1991; also McMichael and Olson unpubl. ms. 1991), Meyer and Miller (1990, 1991, unpubl. ms 1991; also Wyoming Game and Fish Department 1990, 1991), Fredenberg (1992), Hollander and Carline (1992), Newman (1992, unpubl. ms. 1991), Reynolds et al. (1992), Roach (1992), and Taube (1992) have similarly documented substantial PDC-caused spinal injury not only in rainbow trout (up to 98%), but in cutthroat trout (*Oncorhynchus clarki*), brown trout (*Salmo trutta*), brook trout (*Salvelinus fontinales*), northern pike (*Esox lucius*), and walleye (*Stizostedion vitreum*). One agency, the Alaska Department of Fish and Game, has even imposed a moratorium on electrofishing in waters containing large rainbow trout (Holmes et al. 1990; Reynolds pers. commun.). Concern for similar injury to other species, particularly endangered fishes in the Lower Colorado River Basin, was the motivation for this review of electrofishing impacts on fish.

Electrofishing has been one of the more effective and consistently used methods of fish collection in the Glen Canyon Environmental Studies (GCES) program. However, as a result of the controversy generated by Sharber and Carothers' (1988) publication, which was based on work in Glen Canyon National Recreation Area and Grand Canyon National Park, the Aquatic Coordination Team of the GCES and regional offices of the National Park Service and Bureau of Reclamation are concerned about the continued use of electrofishing to capture and monitor endangered and other native fishes such as the humpback chub (*Gila cypha*). The National Park Service is mandated by law to preserve and protect species found within its jurisdiction. It is particularly concerned that extensive electrofishing of spawning aggregations of humpback chub might significantly impact reproduction and survival of the population. Until these concerns are resolved, the Superintendent of Grand Canyon National Park, J. H. Davis, has suggested that electrofishing in Glen Canyon National Recreation Area and Grand Canyon National Park be kept to a minimum and used in such a way as to minimize possible stress and injury to humpback chub (memorandum to GCES program manager, July 12 1990).

The National Park Service needs information to fully evaluate impacts of electrofishing on humpback chub for Section 7 consultation (Endangered Species Act of 1973 and subsequent amendments). Once the nature and degree of electrofishing impacts are identified, it may be necessary to modify electrofishing techniques or limit their application to minimize the problem of physical injury. Alternatives to electrofishing may need to be considered. The Bureau of Reclamation has suggested three phases for acquisition of the needed information. Phase I would be a position paper consisting of a comprehensive literature review and synthesis of existing information on effects of electrofishing and means for reducing adverse impacts. This information would be used to help

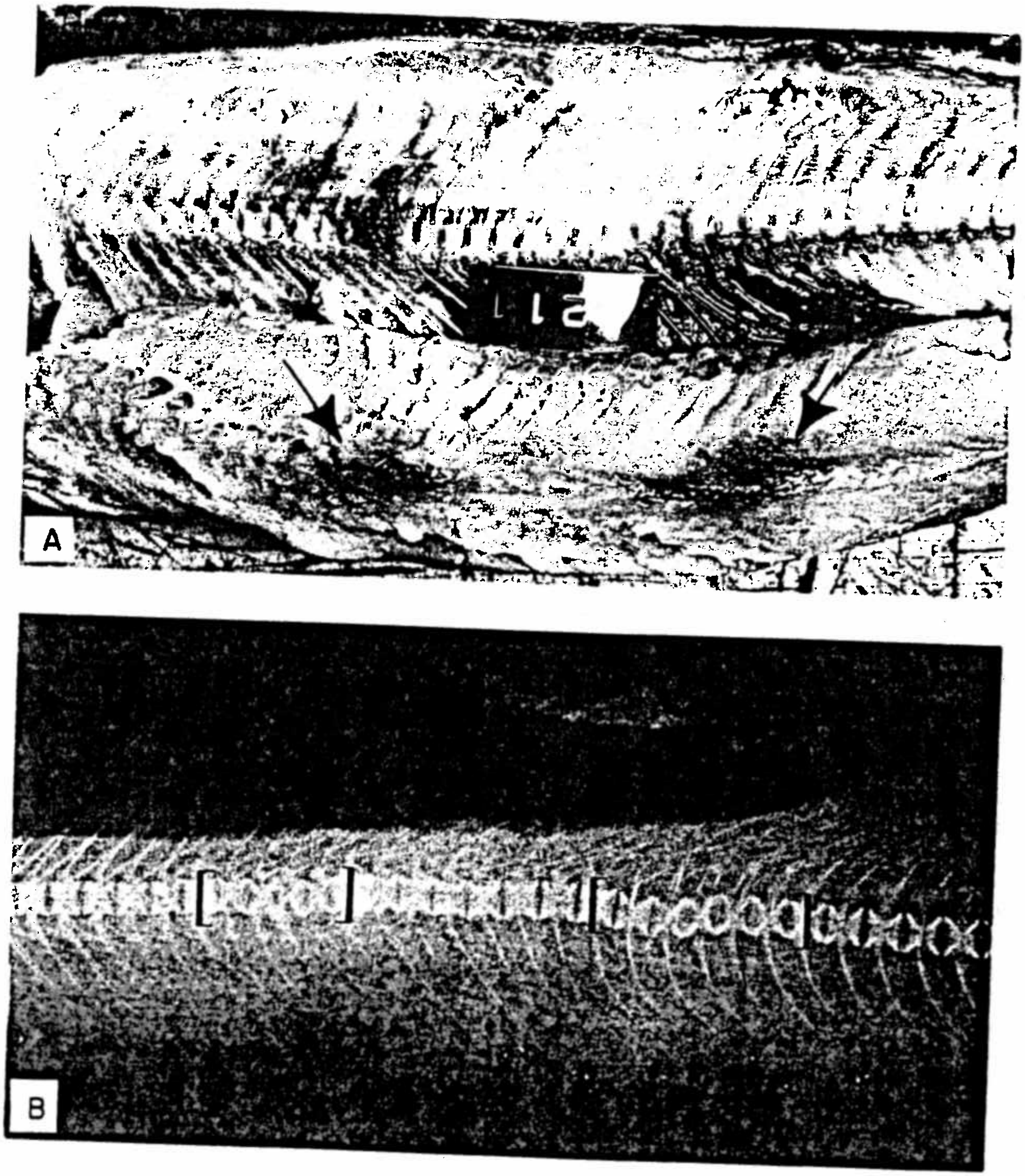

Figure 1. Electrofishing-induced injuries to the spine and associated hemorrhages in rainbow trout (reproduced with permission from Sharber and Carothers 1988, Figure 2). A is a photograph of two injuries exposed by fillet, B is a lateral-view X ray of the same injuries prior to necropsy.

establish interim guidelines for minimizing detrimental effects of electrofishing and direct research to address unanswered concerns and additional means for reducing injury. Phase II would consist of controlled experiments (laboratory and/or field) to answer questions and concerns remaining after Phase I. Phase III would consist of field experiments to verify results or test the effectiveness of techniques developed in Phase II. This report is Phase I, the position paper.

Most of this paper is a synthesis of published information, unpublished manuscripts, technical presentations, regional survey responses, and personal communications with experienced electrofishing personnel and authorities. Based on this synthesis, the remainder of the paper (conclusions) consists of responses to specific questions to be addressed by this investigation, recommendations for minimizing potential electrofishing injury and mortality under present technology (interim policy), and recommendations for research to determine the extent of electrofishing injury to species of concern and fill critical gaps in our understanding of the problem, its causes, and its resolution.

METHODS

Publications on electrofishing and particularly its effects on fish were identified by various means; the recent bibliography by Burridge et al. (1990) and electronic databases were especially useful. Much of the more pertinent literature was obtained and scanned for content. The literature identified for this investigation was catalogued, with keywords and content codes, in a bibliographic computer database (*Reference Manager* by Research Information Systems, Inc., Carlsbad, California). The indexed bibliography in Appendix I is a hardcopy version of the database.

Information derived from the literature was supplemented by data, observations, hypotheses, and recommendations in unpublished manuscripts (mostly works being prepared or considered for publication) and anecdotal accounts through personal communication (see lists of cited sources at the end of this report). Information regarding unpublished and on-going work, as well as personal observations, experiences, and suggestions was solicited through a request printed in *Fisheries* (American Fisheries Society, May-June 1991) and several other fishery-related bulletins and newsletters (Appendix II; approximately 30 responses were received). Several recognized authorities and electrofishing gear manufacturers also shared their knowledge, views, and unpublished manuscripts. Some contacts were made during a special session on electrofishing injuries that was held as part of the July 1991 annual meeting of the Western Division of the American Fisheries Society in Bozeman, Montana. Finally, a questionnaire was prepared to solicit more local observations and recommendations on electrofishing (Appendix II). The survey forms were distributed to researchers working in the Colorado River Basin and fishery biology faculty and students at Colorado State University. Unpublished observations and hypotheses in the following review are used with source permission.

REVIEW AND COMMENTARY

Electricity has been used by humans to kill, anesthetize, capture, drive, draw, tickle (stir), guide, or screen (block, repel) fish since the mid 1800's (Halsband and Halsband 1975, 1984; Hartley 1990; Vibert 1967b). As early as 1863, a British patent was granted to Isham Baggs for electric fishing, but widespread development and use of the technique did not occur until the 1950's. Halsband and Halsband (1975, 1984) provide a particularly detailed history of research on fish in electric fields, especially with regard to German contributions. However, man's technological developments are often modifications or imitations of nature's own. Since before the evolution of modern man, certain species of fish, themselves, had developed powerful electric organs, the discharges of which were probably used, as they are by their modern descendants, to detect and capture prey or ward off predators (Hyatt 1979; Marshall 1966). It is also interesting that the stunning or narcotizing effects of electric fishes were known and used for medical purposes by the ancient Greeks and that the study of electric fishes in the

18th and 19th centuries was instrumental in our recognition of the electrogenic nature of nerves and muscles (Wu 1984).

Most of our knowledge of electrofishing practice, theory, and effects on aquatic organisms is well represented in three European books edited by Vibert (1967a), Cowx (1990), and Cowx and Lamarque (1990); a German volume by Halsband and Halsband (1975, English translation 1984); and a Russian book on electrofishing by Sternin et al. (1972, English translation 1976). A book by Meyer-Waarden and Halsband (1975, German) and a symposium publication edited by Maiselis (1975, Russian with English summaries) also should be included in the list, but English translations are not available. The three European books comprise the published reports and papers of special FAO (United Nations Food and Agriculture Organization, Belgium, 1966) and EIFAC (European Inland Fisheries Advisory Council, England, 1988) symposia. *Fishing with Electricity*, edited by Cowx and Lamarque (1990), can serve as a relatively up-to-date academic text and basic reference but not all the information therein should be treated as fact; there are just too many uncertainties and gaps in our knowledge. Although the book is treated by distributors as a replacement for Vibert's (1967) *Fishing with Electricity*, the latter includes much information not in the new book. Halsband and Halsband (1975, 1984) is also a fine text on electrofishing, but it is based largely on German perspectives, experience, and research and, like Vibert (1967a), somewhat dated. The Russian book is a very detailed treatise on the theory and practice of electrical fishing, including marine applications, based on Soviet research and summaries of world literature. Its appendices include tabulated summaries of fish response thresholds (without source references) and aftereffects; copies of these summary tables are reproduced in Appendices III and IV. A text-type manual is planned for the *Principles and Techniques of Electrofishing* course offered through the Fisheries Academy of the U.S. Fish and Wildlife Service (Temple pers. commun.). Except for the article by Sharber and Carothers (1990) in Cowx (1990), a four-page synopsis in the article by Lamarque (1990) in Cowx and Lamarque (1990), and a few pages in Halsband and Halsband (1975, 1984) and Sternin et al. (1972, 1976), the matter of electrofishing injury and mortality was not discussed extensively in any of these books.

Since the 1988 EIFAC symposium and concurrent publication by Sharber and Carothers (1988), some researchers have begun to verify and further investigate the extent, conditions, and causes of electrofishing-induced spinal injuries (e.g., Sharber et al. unpubl. ms. 1989, unpubl. ms. 1991; Holmes et al. 1990; Wyoming Game and Fish Department 1990, 1991; Fredenberg 1992; and others cited in the introduction). Many biologists across the continent, and probably abroad, now acknowledge that the incidence of electrofishing injuries in otherwise normal appearing specimens might be a serious concern, at least for some environmental conditions, equipment, and species. They are asking: what species and size groups are affected; to what degree are they affected; what equipment, electrical parameters, and techniques are responsible; what specific mechanisms are involved; and what can be done to eliminate or minimize the problem?

Most of these are not new questions. Spinal injury has long been associated with AC fields (Hauck 1949). But in spite of electrofishing's prominent role in fishery research and management, well-designed investigations in response to many of these questions and others regarding the general reactions of fish in electric fields are scarce, often very limited in scope (frequently a by-product of another investigation), and difficult to compare because of differing gear, techniques, environmental conditions, fish, and terminology. With regard to terminology, many researchers and authors fail to make critical distinctions such as those between PDC and continuous, non-pulsed, direct current (DC), peak and mean voltages or voltage gradients, and narcosis and tetany. The design, methodology, and interpretation of results in some studies suggest that the researchers had an inadequate understanding of basic physics and electricity (Sharber pers. commun.). Also, many reports of adverse effects are anecdotal or lack critical data on the circumstances of the observations or experiments. Perhaps mostly as a result of these limitations and deficiencies, publications and reports sometimes seem so contradictory that they appear to follow the law of physics which states that for every action (report), there is an equal and opposite reaction (counter report).

Broader questions are also being re-considered. Biologists are concerned about potential effects of electrofishing injuries on the survival, growth, reproduction, and general well-being of the populations and communities they are studying. They are also concerned about the validity and interpretation of data based on fish collected by electrofishing. Horak and Klein (1967), Spencer (1967), Hudy (1985), and Schneider (1992) reported that electrofishing injuries often heal and are not necessarily lethal or debilitating. Although most fish apparently survive electrofishing-induced spinal injuries, Lamarque (1990) suggested that growth would certainly be impaired. Sharber and Carothers (1988, 1990) noted that we do not know how long fish with electrofishing injuries will survive and suggested that at least for large rainbow trout (the subjects of their investigation) such spinal injuries might bias age, growth, and population studies based on mark-recapture techniques. Sharber and Carothers (1988, 1990) also cautioned that the detrimental impact of such injuries might be very significant for populations of fishes that are already endangered.

Why has electrofishing injury with relatively modern equipment not been recognized as a potentially serious problem until now? Probably because most spinal injuries are **not externally obvious** and can only be detected by X-ray analysis or necropsy. [Necropsy is the dissection and examination of a dead body whereas "autopsy" is specifically the examination of a dead human body. Accordingly, the term autopsy is misused in much of the electrofishing literature.] If captured fish appear to recover sufficiently to swim away and there are no notable external injuries, we typically consider the fish "unharmed" and assume they will continue to grow and behave normally. Schreck et al. (1976) and Whaley et al. (1978) suggested that even recovery from the physiological stresses of electrofishing and handling seldom requires more than a few hours to a day. Also, we often accept some injury or mortality as an unavoidable by-product of most fish collection techniques.

In many sampling situations, electrofishing has been considered the most efficient and least damaging collection technique available. Recognized authorities on electrofishing have emphasized its benign qualities at least when using currents other than AC. Halsband (1967) stated that "the harmlessness of electric current to fish and their food organisms has already been proved on several occasions." In the foreword to their book on electrofishing, Sternin et al. (1972, 1976) suggested that the theory and practice of electrical fishing in recent decades have put to rest concerns about deleterious effects on normal vital activity and natural reproduction of fish. More emphatically, Halsband and Halsband (1975, 1984) stated that "today we are convinced that electrical collecting, repelling, and stunning methods neither cause pain to animals nor injure them internally or externally, (apart from unavoidable exceptions)."

Even now, some biologists (Nehring 1991; Schneider 1992) maintain that years of electrofishing, even with AC (Schneider 1992), has not had a detrimental effect on the specific populations they manage or monitor. Accordingly, they suggest that the occurrence of electrofishing injuries in their situations is either very low or insignificant.

If such injuries do occur in notable numbers but do not significantly affect population size and recruitment, perhaps the concern should be for resource quality. For some fish, spinal injuries result in permanently bent backs and related deformities (Figures 2, 3), sometimes not becoming obvious until well after the electrofishing event. For other fish, spinal injuries might only be revealed by X rays or dissection, possibly on a fisherman's dinner table.

"Brand" or "burn" marks are particularly obvious indications of injury (Figure 4). Fishery workers often consider these usually temporary marks to be a result of direct contact with or close proximity to the electrode, but they also occur on fish netted some distance from the electrode (Lamarque 1990). Some of these marks may indeed be burns from contact with the electrode (Lamarque 1990), but most are the result of intensified melanophore pigmentation in the skin stimulated by spinal injuries and related trauma (Emery 1984; Lamarque 1990; Fredenberg 1992) or hemorrhages in or under the skin (Reynolds unpubl. ms. 1992). Even 25 years ago, Horak and Klein (1967) identified the cause of these marks as internal hemorrhages and possible damage to the vertebrae. Although the presence of brands is almost surely an indication of spinal injury, their absence does not indicate lack of spinal injuries (Fredenberg 1992). Injured fish often show no external signs of injury

The extent of concern over electrofishing injuries in North America is exemplified by the formation of an informal working group on electrofishing injuries within the Western Division of the American Fisheries Society (AFS), special sessions on the matter held during annual meetings of the Western Division in July 1991 (Bozeman, Montana) and 1992 (Fort Collins, Colorado) (abstracts of papers presented at these special sessions were reprinted in the fall/winter 1992 issue of the AFS Fisheries Management Section Newsletter, vol 12, no. 2), and plans for an Electrofishing Injury Network through the AFS Fisheries Management Section. In Europe, a workshop on the harmful effects of electrofishing was planned for spring 1991 in Hull, England, but was canceled due to the Iraqi conflict. It was rescheduled by the EIFAC Working Group on Electric Fishing and held on 21 and 22 May 1992 in conjunction with the 17th Session of EIFAC in Lugano, Switzerland (for details, contact Dr. Ian Cowx, Humberside International Fisheries Institute, University of Hull, Hull HU6-7RX). Until the matter is effectively resolved, electrofishing injuries are likely to be the topic for many more special sessions, workshops, and organizations in the near future.

Manufacturers of electrofishing gear are obviously concerned; they have a vested interest in the technique and have begun developing and marketing equipment intended to help reduce electrofishing injuries. As examples, see the advertisements on both sides of the back cover of *Fisheries* 16(6), November-December 1991. One is for Coffelt Manufacturing's *CPS* or *Complex Pulse System* (a patented pulse train of three rectangular pulses at 240 Hz repeated 15 times per second) which was specifically developed to reduce spinal injuries. The other advertisement is for Smith-Root's *P.O.W.* or *Programmable Output Waveforms* unit which is not intended to reduce injuries itself but allows users to select from a very wide range of patterns or waveforms, including pulse trains, some of which are likely to be less harmful than others.

Even hypotheses regarding the causes and mechanisms of fish responses in electric fields are being re-examined in an attempt to identify and explain specific factors associated with injuries. During the aforementioned session on electrofishing injury held last summer in Bozeman, Sharber (pers. commun.) introduced the "Bozeman Paradigm." His hypothesis is that the observed responses of fishes in electric fields, including muscular seizures resulting in spinal and related injuries, represent essentially the same phases of epilepsy observed when humans and other animals are subjected to electroconvulsive therapy. As will be discussed later, Sharber correlates these epileptic phases—automatism, petit

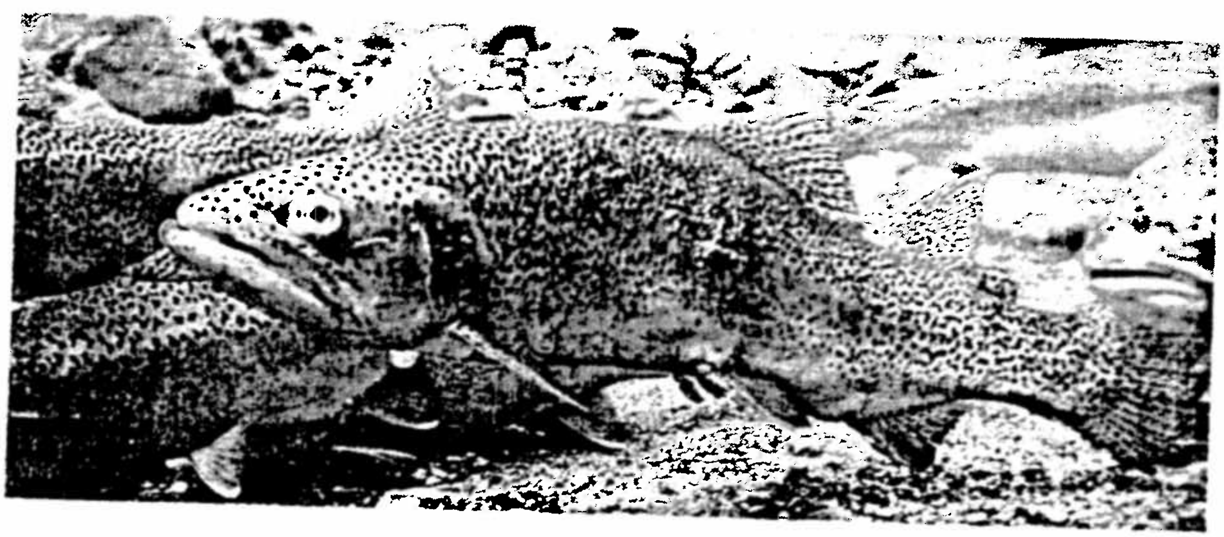

Figure 2. Bent back in rainbow trout caused by electrofishing. (Photograph provided by and reproduced with the permission of M. S. Quinton via W. A. Fredenberg).

mal, and grand mal—with the familiar and well-published descriptions and explanations of electrofishing responses, particularly those he refers to as the "Biarritz paradigm" espoused by Blancheteau et al. (1961), Blancheteau (1967), Lamarque (1963, 1967a, 1990), and Vibert (1963, 1967b) following their intensive investigations at the Biarritz Hydrobiological Station in France.

Unfortunately, many investigations of electrofishing injuries are ancillary to ongoing electrofishing surveys, inadequately supported, or preliminary studies that need follow-up. There is an urgent need for a coordinated program of future electrofishing research. Research should be coordinated towards a specific set of goals to optimize resources at all levels, assure comparability

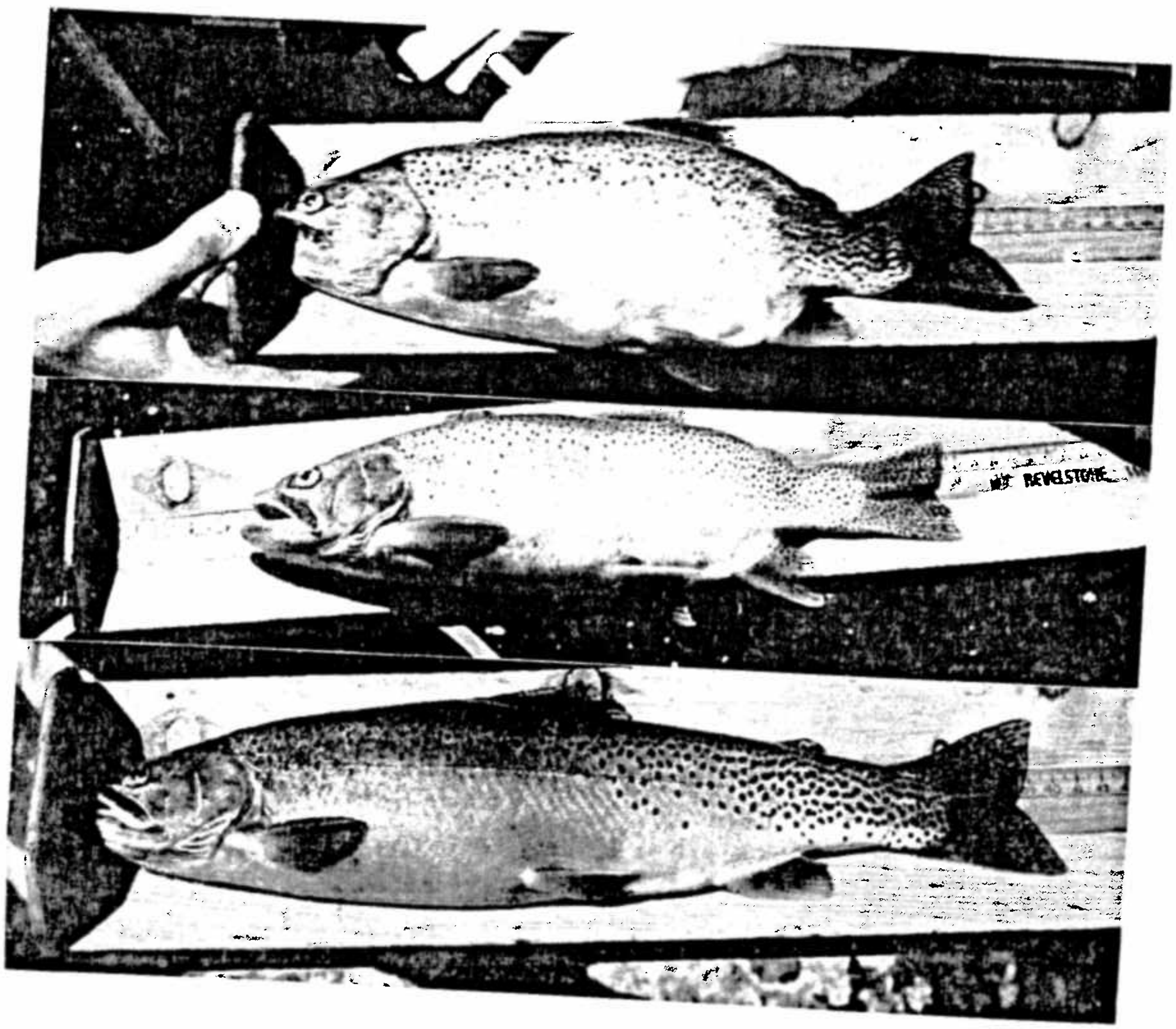

Figure 3. Bent backs and abnormal growth in westslope cutthroat trout (*Oncorhynchus clarki lewisi*, about 38 to 40 cm TL) possibly caused by electrofishing–top and middle specimens; bottom specimen normal for comparison. These were the only obvious deformed fish among 93 trout maintained as brood stock in Kiakho Lake, British Columbia. All fish were originally captured as 1-3 year-old juveniles a few years earlier by stream electrofishing and that event was considered the most likely cause for the deformities. However, biologists sometimes attribute such deformities to other causes. (Photographs provided by and reproduced with the permission of G. Oliver, fisheries biologist, Kootenay Region, British Columbia)

of data, and avoid unnecessary replication of effort. The foundation for such a coordinated effort is a synthesis of what we already know or suspect.

The following synthesis concentrates primarily on the effects of electric fields on fish, particularly injurious and fatal effects, and on various controlling factors. Suggestions for minimizing injurious effects and mortality based on existing information are summarized under conclusions and recommendations.

ELECTRIC FIELDS IN WATER

Electrofishing (sometimes referred to as electric or electrical fishing, electroshocking, or simply shocking), as well as the use of electrical barriers, screens and some forms of anesthesia, depend on the generation of a sufficiently strong electric field around electrodes in water to elicit the desired responses by targeted fishes. The size, shape, and electrical intensity of that field are determined largely by container or basin configuration and dimensions; conductivity of the water and bounding or interspersed substrates; size, shape, and position of the electrodes; and the power and form of current applied through the electrodes. These factors are discussed extensively by Cuinat (1967), Novotny and Priegel (1971, 1974), Halsband and Halsband (1975, 1984), Sternin et al. (1972, 1976), Smith (1989), and Novotny (1990).

Water Conductivity

Water conductivity, its capacity to conduct an electric current, is the most critical environmental factor in defining the strength and range of an electrofishing field. The conduction of electricity in water is an ionic phenomena. Conveyance of electrons from negative to positive electrodes (cathode to anode) to complete an electrical circuit depends on electrolytic reactions at the electrodes and an almost instantaneous chain of ionic movements and interactions in the water between and around the electrodes. Accordingly, conductivity varies directly with ionic content, the dissolved solids, salinity, alkalinity, and pH of water. In nearly pure water which has a very low conductivity, ionization of water itself furnishes a substantial portion of the conducting ions. When electrofishing in very low-conductivity streams, some biologists have found it necessary to artificially increase conductivity by adding salt to water upstream of the sampling area (Lennon and Parker 1958; Zalewski and Cowx 1990). Conductivity is the reciprocal of resistivity (ohms-cm), a term preferred by some authors, especially for very low-conductivity (high-resistivity) waters. Conductivity is usually measured with a conductivity meter as mhos or siemens (S) per cm (usually µmhos/cm or µS/cm; µ = micro or 10^{-6}; mho is ohm spelled backward to indicate the inverse

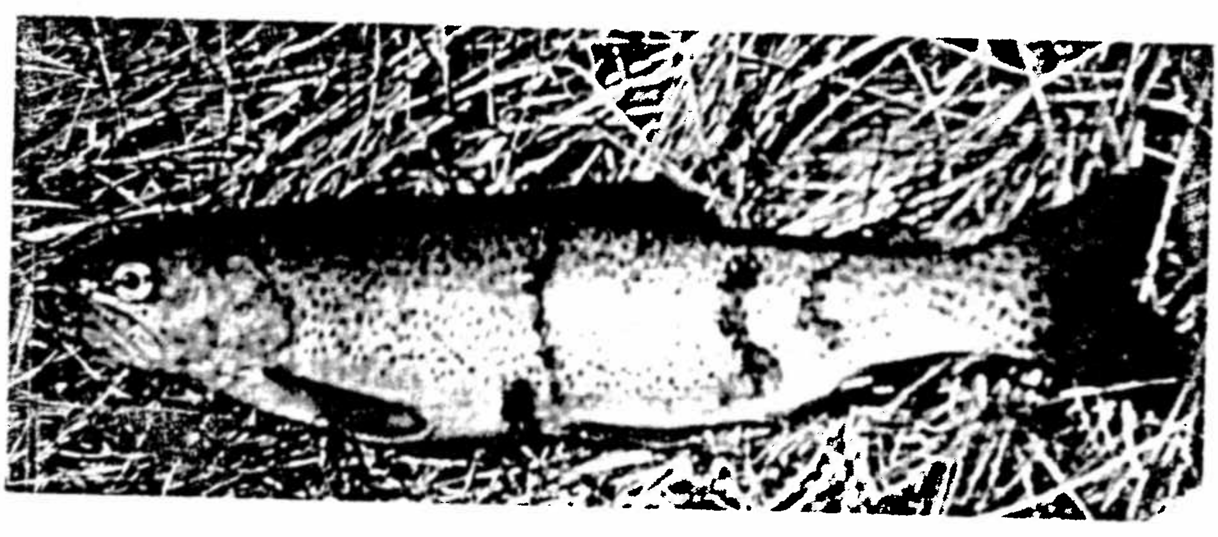

Figure 4. Brands (bruises) in rainbow trout caused by electrofishing. Brands are usually a temporary external manifestation of spinal injury, but injured fish often lack brands. (Photograph provided by and reproduced with the permission of W. A. Fredenberg).

relationship of these units). Siemens is the term approved for the International System of Units and used in the remainder of this report.

Conductivity in natural waters ranges from as low as 5 µS/cm in pure mountain streams (Gatz et al. 1986; Zalewski and Cowx 1990) to 53,000 µS/cm in seawater (Omega Engineering Inc. 1990). The upper limit for potable water is about 1,500 µS/cm (Wydoski 1980). Conductivity in a particular body of water, although generally more-or-less uniform on the same day, can vary considerably from one location to another depending on substrate composition and especially the inflow of tributaries or effluents of highly different conductivities.

Conductivity will also vary directly with water temperature. As temperature rises, water viscosity decreases and ionic mobility and solubility of most salts increase. Rates of change in conductivity depend on ionic content and vary from about 5.2% per °C for ultra pure waters to 1.5% per °C for acids, alkalis, and concentrated salt solutions (Omega Engineering Inc. 1990). For natural waters between 10 and 25°C, the coefficient is approximately 2 to 2.3% per °C. To approximate water conductivities at various temperatures within this range, Reynolds et al. (1988) used the equation $c_2 = c_1/(1.02^{(t1-t2)})$ and Sternin et al. (1972, 1976) $c_2 = c_1/(1 + 0.023(t_1 - t_2))$ where " c" is conductivity and "t" is temperature. Conductivity measures are often normalized to 25°C; it is important to note whether reported conductivities are for the temperatures actually encountered (as is often, but sometimes incorrectly, assumed) or normalized data.

In addition to the transfer of electrons, the process of electrolysis at the electrodes results in the generation of gases and, more importantly, the loss of metal ions from the anode to the water, deposition of metal ions from the water onto the cathode, and formation of metallic compounds such as oxides on the cathode (Sharber pers. commun.). Riddle (1984) suggested that it was not wise to buy aluminum punts (boats) second-hand from electro-fishermen because the gauge of the metal might be substantially reduced. According to Sharber (pers. commun.), this is not a problem when a metal boat is used as the cathode. But when a metal boat is situated in an electric field and not used as an electrode, it has an intermediate electric charge, negative with respect to the anode and positive with respect to cathode. In this case, electrolytic reactions result in both the formation of non-conductive metallic compounds on the boat's surface and the loss of structural metal. Over time, the latter reaction can reduce the structural integrity of the boat. When a boat is used as a cathode, no metal is lost but the non-conductive metallic compounds that form on the boat's surface can decrease its electrical efficiency. This coating can be periodically scraped or sanded away to recover cathodic efficiency, but in doing so, some structural metal may be inadvertently lost. Some researchers switch electrodes periodically to reverse the buildup of metallic oxides (Sharber and Carothers 1988). The effectiveness of this procedure has not been reported.

Field Strength

The responses of fish to electric fields are dependent on the field's strength or intensity (some responses in PDC and AC are also frequency and waveform dependent). Field strength can be described by any of three interrelated and conductivity-dependent terms: voltage gradient (E, volts per unit distance, usually V/cm), current density (J, amperes per unit area of an isopotential surface, usually µA/cm^2), or power density (P, watts per unit volume between isopotential surfaces, usually µW/cm^3). [An isopotential surface lies perpendicular to the field or current lines and is defined by a set of points having the same voltage differential when measured from the surface of the electrode; if the water is of uniform conductivity and unbounded, the electrode is spherical, and other electrodes are sufficiently distant, each isopotential surface will form a shell the points of which are a uniform distance from the surface of the electrode.] Of these quantities, only voltage gradient can be measured directly. The other descriptors of field strength are functions of conductivity (c) and voltage gradient ($J = cE$ and $P = cE^2 = JE$; Kolz, A. L., 1989). Figures 5 and 6 illustrate the relationship between these descriptors of field strength and conductivity. Note that in the middle graph of Figure 5, the curve for voltage gradient becomes asymptotic with the y-axis as conductivity approaches zero and with the x-axis as conductivity approaches infinity, whereas the reverse is true for current density. As a result, the curve for voltage gradient at a fixed power density is

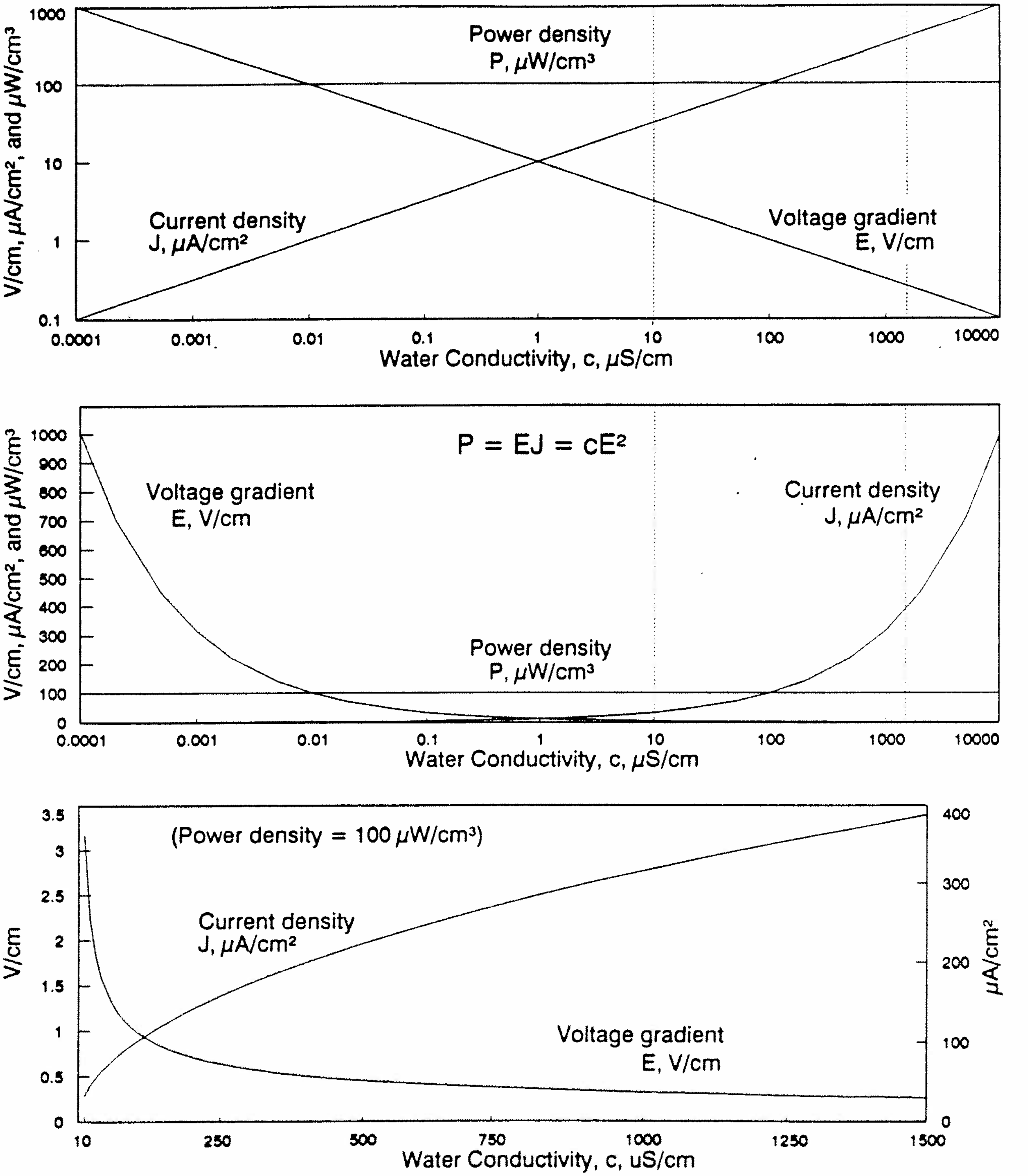

Figure 5. Changes in voltage gradient and current density relative to water conductivity at a constant power density of 100 μW/cm³. The top and middle graphs are the same except both axes are logarithmic in the top graph and only the horizontal axis is logarithmic in the middle graph. Both axes are arithmetic in the bottom graph which covers the range of conductivities typical of freshwater, about 10 to 1,500 μS/cm (seawater is approximately 50,000 μS/cm.); the corresponding ranges in the upper graphs are bounded by vertical lines.

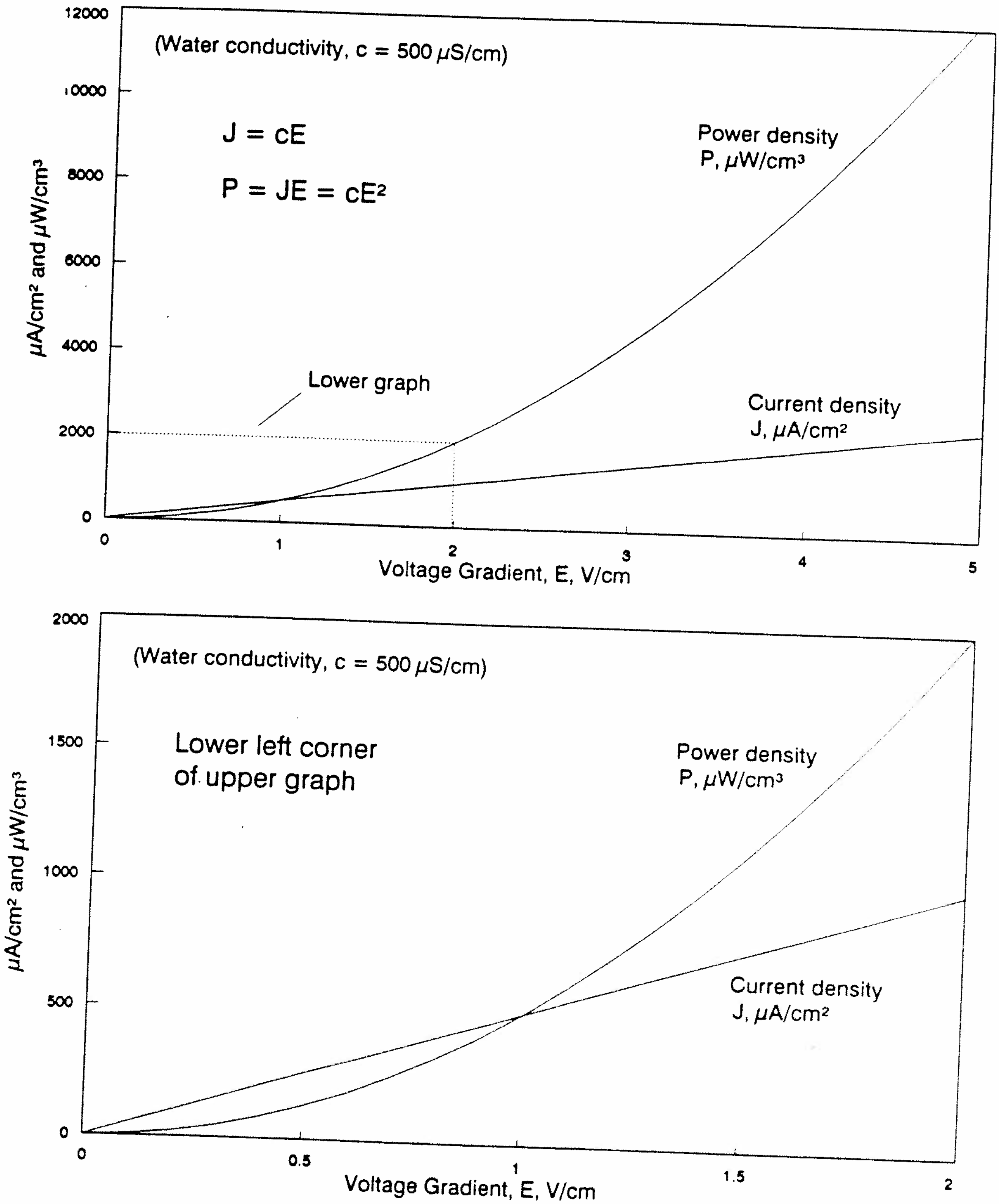

Figure 6. Changes in current density and power density relative to voltage gradient at a water conductivity of 500 µS/cm. For other conductivities, adjust the values along the vertical axis in direct proportion to the change in conductivity (e.g., for half the conductivity, 250 µS/cm, halve the values along the y axis).

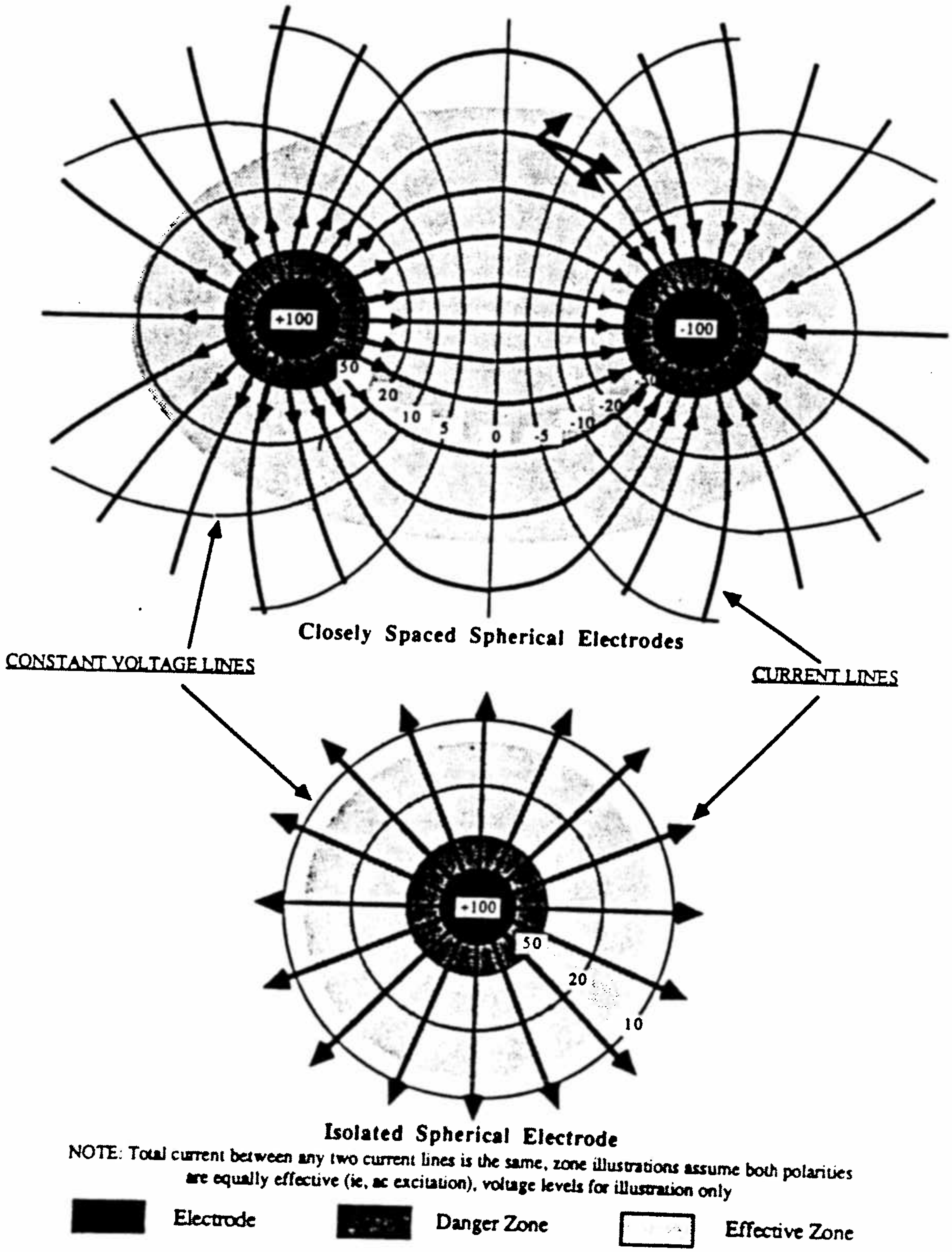

Figure 7. Hypothetical two-dimensional maps of heterogeneous electric fields around and between electrodes (reproduced from Novotny 1990, Figure 3.10). When electrodes are sufficiently far apart, the field about each is essentially isolated as indicated in the lower diagram. Isopotential (constant-voltage) lines are perpendicular to the radiating lines of current.

relatively flat over all but the lower end of the range for freshwaters and practically horizontal for more saline waters (bottom graph, Figure 5).

Peak values of field-strength (e.g., voltage gradients) are probably more biologically significant than mean values in PDC or AC (Kolz and Reynolds 1989; mean and peak values are the same in DC). It is important that researchers and authors document whether field-strength measures (as well as output voltage, amperage, and power) are peak or mean values; the difference can be substantial.

Voltage gradients can be measured with a voltmeter or oscilloscope connected to insulated wires, the tips of which are exposed in the water a fixed distance apart. The maximum voltage gradient or voltage differential measured with this probe will be obtained when the line between the exposed tips is oriented along the field's lines of current. When the probe tips are rotated perpendicular to the lines of current there should be no effective voltage differential and the reading on the voltmeter or oscilloscope should be 0 V. Like voltage-gradient probes, fish are subject to the greatest voltage or potential differential when they are oriented along the lines of current. This is often referred to as "head-to-tail voltage." They are subject to the least voltage difference when oriented perpendicular to the field lines.

Voltmeters specifically designed to yield peak voltage (e.g., peak voltage detectors—Jesien and Hocutt 1990) or oscilloscopes should be used for accurate measurements in PDC (or pulsed AC). The presence of voltage spikes in PDC waveforms may affect readings in some peak voltage detectors. Oscilloscopes, although much more expensive, allow the user to not only document voltage spikes, peak voltages (ignoring spikes), and voltage gradients, but monitor waveform and frequency of the current. The typical voltmeter (or multimeter) works well for measuring peak-voltages in DC and mean-voltages (rms, root mean square) in AC fields, but according to Jesien and Hocutt (1990), such meters cannot accurately measure voltage in PDC or pulsed AC. Fredenberg (pers. commun.) also found that PDC voltage-gradient readings with a standard voltmeter were neither accurate nor consistent.

Some voltmeters can be modified to provide accurate mean voltages or voltage gradients for specific PDC waveforms. Such is the case for at least one commercial instrument and probe designed specifically for measuring voltage gradients in electrofishing fields—the combined field-strength and conductivity meter, *FS/C-III*, built and sold by Micro-Technologies of Idaho (M.T.I., Pocatello). Although this meter provides only mean voltage-gradient readings for only one PDC waveform (50% duty cycle and an unspecified waveform, probably half-sine), peak values for this waveform and either peak or mean voltage-gradient measures for other currents, waveforms, and duty cycles can be calculated by applying appropriate correction factors. For example, in DC fields the manufacturer notes that the meter reads 1.33 times greater than the actual peak value. M.T.I. will recalibrate their meters for specific alternative waveforms and duty cycles. Provisions for peak voltage gradients and user selection of settings for a variety of waveforms and current parameters would make this and other field-strength meters much more flexible and useful.

Heterogeneous and Homogeneous Fields

Because the basins are irregular in shape and electrodes are much smaller than their cross-sectional areas, electrofishing fields generated in rivers, streams, lakes, reservoirs, and most other waters are heterogeneous. In such fields, lines of current can be visualized as radiating from and spreading widely around and between the electrodes (Figure 7). Field strength is greatest next to the electrodes and decreases to barely perceptible levels as distance from the electrodes increases, even in the area between anode and cathode when sufficiently separated. The actual field strength encountered by a fish in a heterogeneous field depends on the fish's location relative to the electrodes.

Homogeneous fields are typically restricted to laboratory settings in troughs with a constant cross-sectional profile and electrodes approximating that profile squared at each end of the desired field. In homogeneous fields, the current flows parallel to the sides of the trough directly from one electrode to the other. This arrangement provides a constant voltage gradient, current density, and power density between the electrodes.

Controlled experiments in homogeneous fields eliminate many of the electric-field variables that are encountered in natural waters. This greatly

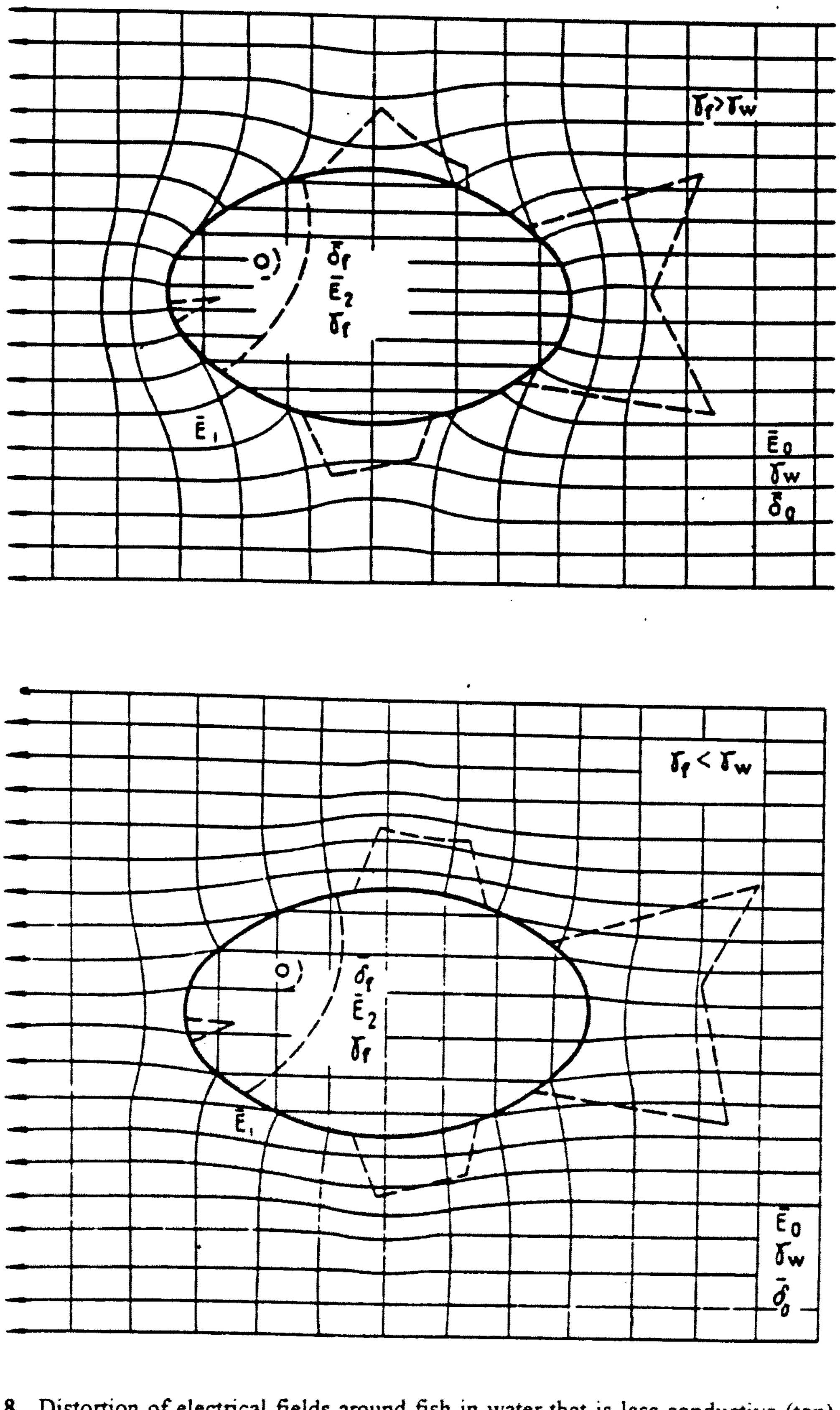

Figure 8. Distortion of electrical fields around fish in water that is less conductive (top) and more conductive (bottom) than the fish (reproduced from Sternin et al. (1976, Figures 77, 78).

simplifies conditions for the experiment and facilitates determination of cause and effect. But results may be difficult to extrapolate to normal electrofishing operations.

Bounding Substrates and Interspersed Objects

Bounding surfaces or substrates of a basin define the body of water in which an electric field is generated. Depending on their electrical properties or conductivity, they also have an effect on the field in and beyond the water. The conductivity of bottom substrates can vary considerably with location, even in the same body of water. Haskell (1954) and Zalewski and Cowx (1990) reported that substrates of fine particles and organic debris are more conductive than those of coarse gravel and rubble. Because of substrate and interstitial water conductivity, electric fields can extend well into the bottom substrate and even onshore. Riddle (1984) suggested that a person standing barefoot on a bank could be shocked. Some of the first electrofishing systems in the United States used AC with one electrode or electrode array implanted in the ground along shore (Haskell 1940, 1950, 1954). Smith (1991) described an experimental electric shark barrier that also incorporated electrodes implanted onshore rather than directly in the water.

Bounding surfaces and interspersed objects that are more conductive than the water tend to concentrate the current and thereby reduce field strength near that surface or object. Conversely, the field is intensified along or around less conductive media including the air at the surface (Zalewski and Cowx 1990). As noted by Haskell (1954) and many other authors since, fish themselves distort the field in their immediate vicinity if they are more or less conductive than the water (Figure 8).

Riddle (1984) recommended that metal boats not be used for electrofishing because they can have a large effect on the field. He suggested that if a conductive vessel is positioned between the electrodes, it would interfere with the field (concentrate the current) and might adversely affect electrofishing efficiency, presumably by altering the size and shape of the effective field. This idea seems to have been overlooked in much of the literature on boat electrofishing, although some, especially earlier, authors strongly discouraged use of metal boats for safety reasons (Goodchild 1990, 1991). Interestingly, with appropriate equipment and wiring, some of today's electrofishing systems use aluminum boats themselves as cathodes; others use fiberglass vessels with metal plates mounted on the bottom as cathodes (Vibert 1967b).

Size, Shape, and Position of the Electrodes

According to Novotny (1990), the electrodes are the most crucial part of an electrofishing system. Their size, shape, surface area, and spacing, along with water conductivity, determine the electrical resistance of the system and, for a specified power output, the distribution of the current (field intensity) and size of the effective field. Electrode systems that are inappropriate for the power supply and waters to be sampled can lead to poor electrofishing results or unnecessary harm the fish. Novotny and Priegel (1974) listed the following characteristics as desirable for an effective electrode system:

- Establishment of the largest region of effective electric current distribution in the water to be sampled.
- Avoidance of local regions of unnecessarily large current densities which waste power and are potentially harmful to fish.
- Adjustability to meet changes in water conductivity.
- Ability to negotiate weeds and obstructions.
- Ease of assembly and disassembly.
- Avoidance of unnecessary disturbance to water to permit easy visual observation of fish.

For electrodes spaced sufficiently far apart (more than several radii in the case of spherical electrodes—Novotny 1990; 10 to 20 radii for rings—Smith 1989), the distance between electrodes no longer has a significant effect on electrode or system resistance and the fields around each electrode are effectively independent. The water outside well-separated anodic and cathodic fields is considered to be at "ambient potential" because its electrical potential does not vary significantly and its voltage gradient is nil (Cuinat 1967). Fish that remain in water of ambient potential, even between the electrodes, are theoretically unaffected by the

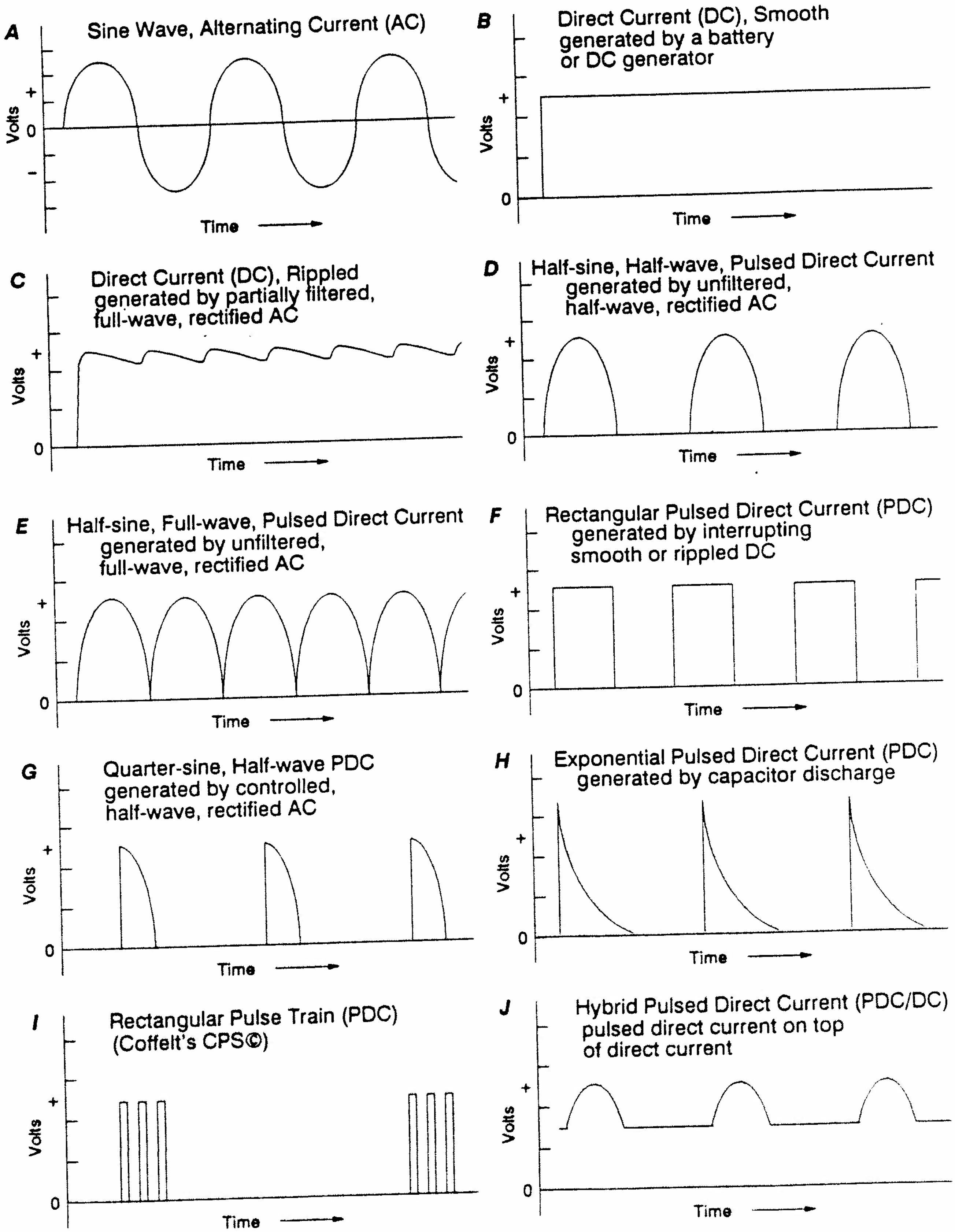

Figure 9. Selected waveforms used in electrofishing.

electrofishing operation (like people working on a metal boat used as the cathode). The level of ambient potential relative to the electrodes depends on the power output, total resistance (sum of anodic and cathodic resistances), and the ratio of anodic to cathodic resistance. When cathodes are much larger than anodes, most of the total potential between electrodes is associated with the anode, the voltage differential between ambient potential and the cathode is relatively small, and voltage gradients near the cathode are much lower than near the anode.

The size, shape, configuration (e.g., single or multiple electrode arrays) and relative position of the electrodes should be selected according to the available power output, water conductivity, and desired distribution of current in the water. Novotny (1990) emphasized that "The most common electrode problem is that the electrodes are simply too small . . . ." At the same voltage output, the larger the electrode, the less its electrical resistance in water, the lower the maximum field intensity immediately around it, the smaller the zone of tetany , and the larger the effective field (greater the range). Sometimes the zone of tetany can even be eliminated. Increasing the number of anodes or cathodes in a system has a cumulative effect similar to increasing the size of an individual electrode (the effect is maximized when multiple electrodes are well separated). Maximum size or number of anodes or cathodes is dictated largely by practical considerations (e.g., maneuverability, transportability, interference with netting). It can also be limited by the maximum power output of the generator, especially in highly conductive waters. Electrode resistance varies inversely with either electrode size (available surface area) or water conductivity. At constant applied voltage, reductions in total electrical resistance result in increased current, sometimes enough to overload the generator. When water conductivity is high, the size of the electrodes must sometimes be reduced to prevent such an overload.

Spherical electrodes are generally considered superior to other shapes (e.g., cables or narrow cylinders). Electric fields generated immediately around spheres are uniform and without the hot spots (localized regions of higher intensity) produced near the corners and edges of many other electrode shapes. Novotny and Priegel (1974) and Novotny (1990) noted that except near their surfaces, circular and ring-like electrodes, including dropper arrays, produce fields similar to those produced by spheres.

In DC and PDC systems, the desired electrofishing responses are generally produced only in anodic fields, whereas fish tend to be repulsed by cathodic fields. However, some adverse effects may be as great or greater in cathodic fields. Jesien and Hocutt (1990) found that channel catfish in homogeneous fields are more sensitive to tetany when facing the cathode than when facing the anode. To minimize cathodic effects on fish, cathodes should be as large as practical. As noted above, this will also maximize potential in the anodic field and reduce the overall electrical resistance of the system. In systems with cathodes much larger than anodes, the very low voltage differential between the cathode and soil and water in vicinity reduces the risk of severe shock or electrocution to people or animals that inadvertently approach or touch the cathode (Smith 1989). Because cathodic resistance for well separated electrodes is halved each time the surface area of the cathode is doubled, Smith (1989) suggested that 10 m^2 is a practical limit to the size of the cathode.

Electrofishing Currents and Waveforms

Electrical currents are of two principal types: bipolar or alternating currents characterized by continually reversing polarity and movement of electrons (AC; Figure 9A) and unipolar or direct currents characterized by movement of electrons in one direction. More specifically, the term DC refers to unipolar currents that are continuous and relatively constant in voltage (Figures 9B, 9C). Both AC and DC can be periodically interrupted or pulsed. Although pulsed AC (e.g., Jesien and Hocutt 1990) is seldom used for electrofishing, several variations of pulsed DC (PDCs) are very popular and typically used with boat systems. PDCs are characterized by frequency (Hz—Hertz, cycles or pulses per second), pulse width (time power is applied during each pulse cycle, usually expressed in ms, milliseconds) or duty cycle (time power is applied per cycle, expressed as a percent of cycle time), shape or waveform (e.g., rectangular, exponential, half sine, and quarter sine), and pattern (either a uniform frequency or secondarily interrupted at much slower frequencies to produce bursts, packets, or trains of pulses). The frequency and waveform of AC can also be varied. However, for electrofishing purposes AC usually consists of the standard sinusoidal waveform at frequencies of 50, 60, 180, 300 or 400 Hz depending on generator speed and whether the generator is a single-phase or three-phase unit (Novotny and Priegel 1974; Novotny 1990).

DC in modern electrofishing is usually produced by conditioning power from an AC generator, or a battery and invertor, with transformers, rectifiers, and filters (Novotny and Priegel 1971, 1974; Novotny 1990). However, DC produced by filtering rectified current from an AC generator tends to be more rippled than that produced by true DC generators (Figures 9B, 9C). DC generators are heavier, more expensive, less flexible in voltage control, and less reliable than AC generators with comparable power ratings. DC produced by a three-phase AC generator is already relatively smooth and requires much less conditioning than that produced by a single-phase AC generator.

Rectified but unfiltered, sinusoidal, single-phase AC produces a half-sine PDC at either the same or twice the AC frequency depending on whether the current is half- or full-wave rectified (Figures 9D, 9E). Other PDC waveforms are produced from either filtered or unfiltered rectified AC by use of mechanical or electronic choppers (pulsators). Electronic choppers utilize transistors, thyristors, and (or) capacitors to achieve the desired waveforms. Rectangular waveforms, often referred to as square waveforms, are perhaps the most flexible and commonly used PDC (Figure 9F). Other common PDC waveforms produced by choppers include quarter-sine and exponential (capacitor-discharge) waveforms (Figures 9G, 9H). Some very flexible electrofishing systems offer AC, DC, and PDC, the latter with variable pulse waveforms, frequencies, and widths or duty cycles. As frequency in a PDC is increased, a constant duty cycle results in proportionately shorter pulse widths, whereas a constant pulse width results in a greater duty cycle. Some systems allow or incorporate secondary switching or interruption of PDC or AC to produce short trains or bursts of the desired waveforms at lower frequencies (e.g., University of Wisconsin Engineering and Technology Center's *Quadrapulse*, Smith-Root's *P.O.W.*, and Coffelt's *CPS*; Figure 9I). Such pulse trains were suggested for consideration by Haskell et al. (1954) nearly 40 years ago. Through various manipulations of the current, DC and PDC have even been hybridized to effectively produce a PDC on top of DC (Vincent 1971; Fredenberg 1992; Figure 9J). In such currents, the pulses drop only to a preset minimum voltage level when switched off rather than to 0 V. Strongly rippled DC (weakly filtered, rectified AC) could be considered as a hybrid current.

The various PDC waveforms generated by electrofishing control boxes are sometimes characterized by variations on the expected shape (Jesien and Hocutt 1990) or anomalies such as spikes at the leading or trailing edges of rectangular-waveform pulses (Fredenberg 1992) and small, rounded, secondary pulses immediately following exponential-waveform pulses (Sharber and Carothers 1988). Jesien and Hocutt (1990) noted that nominally rectangular PDC waveforms generated by their equipment changed shape as water conductivity increased. At conductivities of about 100 µS/cm, the trailing edge was not perpendicular and the voltage level was not constant throughout the pulse. At 1000 µS/cm an exponential-like voltage spike became evident and by 10,000 µS/cm it was especially prominent. In contrast, they found that characteristics of their pulsed AC waveforms remained constant. Voltage-spike anomalies such as those sometimes associated with rectangular waveforms are usually of such short duration that they are not likely to have any physiological effect on fish or other vertebrates (Sharber pers. commun.). Haskell et al. (1954) noted no significant improvement in responses by fish subjected to a 1-Hz (80% duty cycle), rectangular waveform with a high initial peak (interpreted here as a spike) than for a similar waveform without the spike. However, other anomalies may affect fish response. For example, Sharber and Carothers (1988) suggested that the small secondary pulse in their 60 Hz exponential waveform was of sufficient voltage near the anode to effectively produce a 120 Hz mixed waveform that enhanced the immobilization of fish. Because output waveforms are not always as expected according to control box settings, it is important to periodically calibrate, verify, and document waveform in the output circuit with an oscilloscope, especially when operating in waters with highly variable or differing conductivities.

An noted in the discussion of field strength, it is important to distinguish between mean and peak power, voltage, or current. At the same mean power output (watts, the product of voltage and current; W = V x I), peak power and field intensity for AC and PDC are much greater than for DC. For smooth DC, peak and mean voltage (and power) are the same. For sinusoidal, single-phase AC, mean or root mean square (RMS) voltage is approximately 71% of peak voltage. For PDC, the relationship between mean and peak voltage varies with both waveform and duty cycle. The mean voltage for rectangular PDC varies directly with duty cycle (for 50% duty cycle, "on" time, mean voltage and power will be half the peak).

Based on published literature and personal communications, authors and biologists frequently fail to note the type and form of current used. Even when noted, some descriptions of the current are misleading. PDC is often simply referred to as "DC" reflecting its unipolar but not its pulsed nature. Also, referring to its typical origin via an AC generator, PDCs are sometimes incompletely called "rectified AC" (which more specifically refers to either of the two half-sine PDC waveforms or, when filtered or originating from 3-phase AC, rippled DC). Even the term "pulsed AC" has been improperly used for PDC.

RESPONSES TO ELECTRIC FIELDS

As in water, ionic conductivity is responsible for electric currents in the blood and interstitial fluids of living tissues (Sternin et al. 1972, 1976). But the transmission of electricity to and deep within the body of a fish is a complex affair. The tissues and membranes have different and sometimes variable electrical qualities (e.g., conductivity, capacitance, inductance, and impedance; Sternin et al. 1972, 1976; Sharber pers. commun.). Skin, for example, is especially resistive and rapidly dissipates much of the electric current applied to it as heat. Some of the electrical energy that is transmitted across skin and other tissue membranes is transferred by capacitance. With electrolytes on both sides of a membrane (e.g., water on one side and interstitial fluids and blood in capillaries on the other side of skin), the membrane functions somewhat as a dielectric in an electrical condenser and allows a momentary current across the membrane only as applied voltage is switched on, off, or suddenly increased or decreased. No current is transmitted by capacitance when the applied voltage is constant; therefore in PDC, the amount of power transmitted by capacitance varies directly with frequency. Direct electrical stimulation of afferent nerves probably also occurs through various external sensory structures in the skin, possibly including the lateral line canal system. Although not mentioned in the reviewed literature, the gills, which are the primary sites for ionic exchange, might also have a significant role in the transmission electrical current.

Neurological responses to stimuli, nerve impulse transmission, and muscular actions in animals are electrochemical phenomena. In accord with the "all or none" principle of individual nerve response, each level of reaction requires a stimulus of a specific minimum strength. That threshold must arrive quickly and be maintained for a minimum time. However, if a series of stimuli below the threshold level for nerve response are received over a sufficiently short period of time, their effect may be cumulative and still cause the nerve to respond according to the principle of temporal summation (physiology textbooks; Wydoski 1980; Emery 1984).

Lamarque (1967a) summarized several pertinent concepts of nerve or muscle excitation in a DC field. Quoting Lamarque, those concepts are:

1. At a certain threshold, direct current initiates and maintains nerve or muscle excitation by the "autorhythm of excitation" (*see* Fessard 1936 and Monnier 1940).
2. Short nerves in an electric field are excited at a higher value of current than long nerves (Laugier 1921).
3. The greater the angle between a neurone in an electric field and the direction of current flow, the greater the current necessary to excite it (Fick, cited by Charbonnel-Salle 1881).
4. A neurone can only transmit its excitation to another neurone in the soma-axon direction.
5. [With] the stimulus being produced by catelectrotonus at the cathode, an excitation can be conveyed to the next structure only if the cathode is on the

soma side with regard to the axonic endings (normodromic stimuli).

6. Inversely, if the anode is on the soma side with regard to the axonic endings, the soma anelectrotonus can block a normodromic stimulus from another structure, and thus create an inhibition.
7. Nerve or muscle structures of a fish in an electric field can be excited or inhibited *in situ* since the fish body has itself become an electric field. According to the potential values, certain structures will be excited on account of their length (2), or their position (3); others will be inhibited (6), and yet others preserved from the action of current.

Lamarque (1967a) also noted that nerve interaction with PDC is further complicated by ". . . very complex physiological processes, such as chronaxies, spatial and temporal summations, synaptic delays, excitatory post-synaptic potential . . ., polarity inversions due to openings of the circuit, etc."

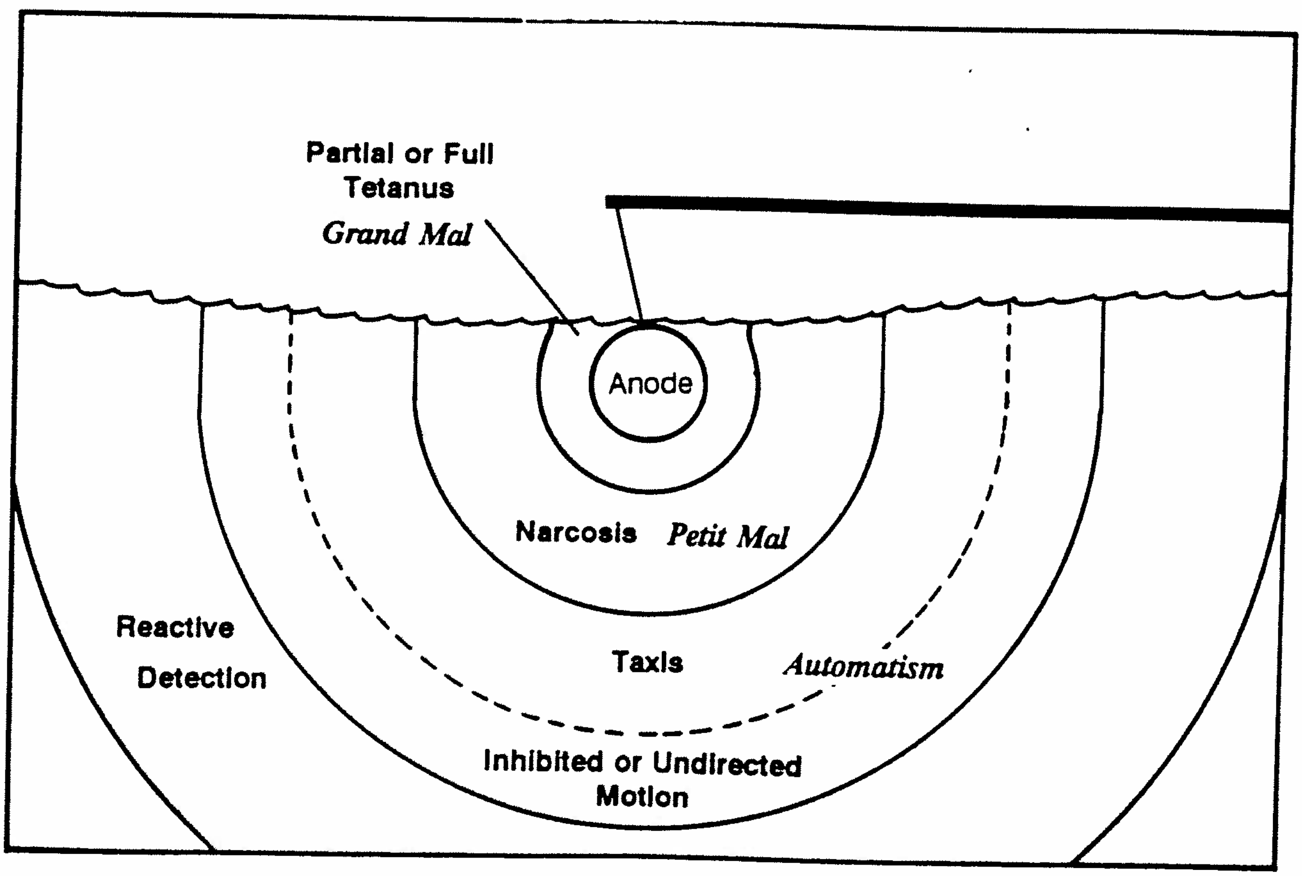

Figure 10. Major intensity-dependent electrofishing response zones. The outer boundaries of zones are more-or-less hemispherical shells around the anode that represent field-strength thresholds for the associated responses. Shape of the inner zones would be affected by the type of anode and shape of the outer zones by close proximity to the cathode, boat, shore, or bottom. Actual and relative sizes of the zones are specimen dependent (species, size and condition) and vary with output power, electrode size, and environmental conditions. Labels in italics represent corresponding phases of epilepsy as suggested by Sharber (pers. commun.). Zones of taxis, narcosis, and tetany represent the effective range for fish capture.

Vibert (1963), Blancheteau (1967), and Lamarque (1963, 1967a, 1990) explained the various responses observed in their experiments at the Biarritz Hydrobiological Station in France based on the above principles. However, some of their hypotheses are difficult to understand and questioned by other researchers (Hüme 1984; Sharber pers. commun.). How their explanations fit in the context of Sharber's epilepsy-response hypothesis, and vice versa, has yet to be explored. Certainly the observed results of the Biarritz experiments are valid under the conditions they were performed. There is likely some truth in the interpretation of responses by both paradigms. A better understanding of the physiological mechanisms involved might be helpful, if not necessary, to determine fields, currents, and conditions that will optimize desired electrofishing responses and (or) minimize adverse effects.

Because the phases of epilepsy are disorders of cerebral function, Sharber (pers. commun.) suggested that all or most of the electric-field responses observed in fish are due to over-stimulation of the central nervous system at various levels, either directly to the brain or short-circuited through the spinal cord. However, other researchers, including Haskell et al. (1954), Vibert (1963, 1967b), Lamarque (1967a, 1990) and Wydoski (1980), concluded that the various responses elicited in fish by an electric field are the result of direct stimulation of not only the central nervous system, which controls voluntary reactions, but also the autonomic nervous system, which controls involuntary reactions, and the muscles themselves. Haskell et al. (1954) and Lamarque (1967a, 1990) demonstrated that tetany in DC and muscular bends of the body toward the anode upon circuit closure in DC, or repeatedly in PDC, can be induced by direct over-stimulation of efferent nerves or nerve endings associated with the muscles. In those experiments, either the efferent nerves were severed from the spinal cord, or the spinal cord was destroyed or removed prior to electric-field exposure. The muscular bends of the body often resulted in movement towards the anode.

Certain responses to electric fields, such as movements toward an electrode, are not unique to vertebrates or even organisms with nervous systems per se. Even individual cells respond. Halsband (1967) noted that carp (*Cyprinus carpio*) and trout erythrocytes placed in a powerful electric field (1000 times more current density than used in electrofishing) first moved towards the anode (cataphoresis), then changed shape from oval to round, and finally disintegrated.

Major Intensity-Dependent Responses

Figure 10 illustrates the sequence of major responses generally observed for fish in electrical fields as field intensity increases toward the anode. Except for their relationship to epileptic responses and the distinction between narcosis and tetany (an important distinction overlooked in much of the literature), most of these responses were documented as early as the 1920s (e.g., Scheminzky 1924 according to Lamarque 1990). During their studies of fish responses in DC, Vibert (1963) and his associates at the Biarritz Station found that not all fishes exhibited the same set of responses they observed for brown trout and European eel (*Anguilla anguilla*) (Table 1). Vibert (1963) suggested that there is ". . . a sort of competition between the reaction to the particular electric stimulus and the general behavioral response to normal ecological stimuli." The meaning of "competition" in this quote is unclear; perhaps Vibert meant interaction or relationship. The Biarritz researchers also reported that some responses are different in other currents. Lamarque (1990) specifically warned that because of the dynamic behavior and unlimited types of PDC available, responses of fish in PDC are quite different from those in DC and that to confuse them would lead to considerable misunderstanding of electric fishing procedures.

Based on either laboratory or field observations, other researchers have reported results that contradict the Biarritz observations and sometimes each other. For example, in PDC fields, the Biarritz researchers observed anodic taxis (and tetany) in trout (brown or rainbow) and European eels but no narcosis (100 Hz, 1-ms pulses), whereas Kolz and Reynolds (1989) in experiments with goldfish (*Carassius auratus*) observed narcosis but no taxis (50 Hz, 2-, 5-, and 10-ms pulses). Yet, in practical electrofishing operations, it is the strength and range of both responses, taxis and narcosis, that make PDC so popular and useful. Taxis towards the anode is also the key to electrofishing with DC, but Haskell et al. (1954) reported that, even under uniform laboratory

Table 1. Reactions identified in homogeneous fields of direct current (modified from Table 1 of Lamarque 1967). Star (★) indicates reaction observed, dash (—) not observed, and shading not studied.

V/cm[a]	Reactions[b]	Species[c]															
Fish facing anode		Ro	Sk	Ee	Ca	Gu	Te	Go	Br	Ra	Sy	Bu	Ce	Ci	Cl	Pl	So
	First reactions[d]			★	★	★	★	★	★	★	★			★	★		
0.10	Jerks of head		—	★				★	—	—	—	★		—	★	★	★
↓	Inhibition of swimming			★	★			★	★	★	★		★	★			
↓	Forced swimming[e]	★	—	★	★	★	★	★	★	★	★		★	—	★	—	—
↓	Galvanonarcosis	★		★	★	★	★	★	★	★	★	★	★	★	★		
↓	Protonos		★	★							★					★	★
↓	Bending of fins				★	★	★	★	★	★	★		★	★	★		
↓	Tetanus of maxillaries			★			★	★	★	★				★	★		
↓	Tetanus of gill covers				★	★	★	★	★	★				★	★		
↓	Quivering of tail, sagittal plane								★	★						★	★
↓	Pseudo-forced swimming			★					★	★				★			
↓	Tetanus of body, nervous origin			★					★	★							
↓	Opistotonos		★	★							—					★	★
1.25	Tetanus of body, muscular origin			★													
	Body pigmentation[f]			★				★	★	★				★			
Fish facing cathode		Ro	Sk	Ee	Ca	Gu	Te	Go	Br	Ra	Sy	Bu	Ce	Ci	Cl	Pl	So
0.10	First reaction[d]			★	★	★			★	★	★		★		★		
↓	Straightening of fins				★	★	★	★	★	★			★		★		
↓	Cathodic galvanotaxis		★	★				★	★	★	★			★	★	★	★
↓	Half turn towards anode			★	★	★	★	★	★	★	★		★	★			★
↓	Tetanus of body, nervous origin		★	★	★	★	★	★	★	★		★	★	★	★	★	★
↓	Maxillary spasms			★	★			★	★	★	★						
↓	Opistotonos		★	★					★	★	★				★	★	★
1.25	Tetanus of body, muscular origin			★													
	Discoloration of body[f]			★				★	★	★				★	★		
Fish first across field		Ro	Sk	Ee	Ca	Gu	Te	Go	Br	Ra	Sy	Bu	Ce	Ci	Cl	Pl	So
0.14	Temporary anodic curvature[d]		★	★	★	★		★	★	★			★	★		★	★
	Temporary cathodic curvature[d]			★					★	★							
0.35	Sustained anodic curvature		★	★	★	★	★	★	★	★			★	★	★	★	★
	Fin straightening on anode side, fin bending on cathode side					★			★	★							

[a] Approximate variation of voltage-gradient thresholds.

[b] Main reactions are underlined.

[c] Ro - Roussette (Scyliorhinidae); Sk - Skate (Rajidae); Ee - Eel (*Anguilla anguilla*, Anguillidae); Ca - Carp (*Cyprinus carpio*, Cyprinidae); Gu - Gudgeon (*Gobio, gobio*, Cyprinidae); Te - Tench (*Tinca tinca*, Cyprinidae); Go - Golden fish (Cyprinidae ?); Br - Brown trout (*Salmo trutta*, Salmonidae); Ra - Rainbow trout (*Oncorhynchus mykiss*, Salmonidae); Hi - *Hippocampus* sp. (Syngnathidae); Bu - Bullhead (*Cottus gobio*, Cyprinidae); Su - Sunfish (*Lepomis* sp. ?; Centrarchidae); Ti - Tilapia M (*Tilapia mossambica* ?; Cichlidae); Cl - *Callionymus* sp. (Callionymidae); Pl - Plaice (*Pleuronectes platessa*, Pleuronectidae); So - Sole (*Solea vulgaris* ?; Soleidae).

[d] *First reactions of fish facing anode; transient anodic curvature.* These reactions occur only at closing the current. They are thus more concerned with *interrupted* current [PDC]. By contrast, the "first reactions" of fish facing the cathode take place at the same threshold, no matter what the conditions of potential input are.

[e] *Forced swimming.* This reaction does not occur with flatfish, which just flatten themselves on the bottom of the tank. In the case if *Callionymous* and *Hippocampus*, this swimming is induced by pectoral or dorsal fins.

[f] *Body pigmentation, discoloration.* These reactions were not thoroughly studied.

conditions, the response was very erratic; certain fish were quickly drawn to the anode but others exhibited only partial or no taxis. Despite reports to the contrary, Sharber (pers. commun.) maintains that the threshold levels and intensity of the various responses might differ (perhaps accounting for at least some of the observed differences), but that the general responses of fish to an electric field are essentially the same regardless of whether AC, DC, or PDC is used.

The responses indicated in Figure 10 are those expected of fish in DC and possibly all electric fields when facing the anode (or either electrode in AC). According to the "Biarritz paradigm", responses and thresholds differ when fish face the cathode or are perpendicular to the lines of current (Table 1). Changes in other environmental or experimental conditions may also affect fish responses. The Biarritz experiments were conducted in homogeneous fields. Whether responses or thresholds specific to fish facing in either direction (toward the anode or cathode) would differ in a heterogeneous field might depend on whether the fish are closer to the anode or the cathode (the matter was not addressed in literature reviewed for this report). Vibert (1963) and Northrop (1967) noted that under field conditions, it is impossible to distinguish each of the responses documented in laboratory experiments, especially in flowing water or a moving field where fish are continually reoriented relative to the lines of current and can be moved quickly from one response zone to another.

Response Thresholds

In most electrofishing situations the field is heterogeneous with field intensity highest at the electrode surface and decreasing geometrically from that surface to barely perceptible levels a few meters away. The outer boundary for each response zone illustrated in Figure 10 represents the field intensity (i. e., voltage-gradient, current-density, or power-density) threshold for that response. The specific values for these thresholds vary with water conductivity and temperature, electric-field waveform and frequency, and the conductivity of the fish. The electrical conductivity of a fish depends on the species, size, shape, condition, surface area, and possibly even size of scales (Whitney and Pierce 1957; Halsband 1967; Emery 1984). The zones shrink or expand for individual fish according to the fish's orientation in the field. As suggested above and in Table 1, not only the threshold but the nature of the response can vary with orientation. A fish in taxis when facing the anode might at the same location be only in the zone of reactive detection when oriented perpendicular to the lines of current. In the latter situation the fish would retain voluntary control of its movements and could dart sufficiently away to escape future influence by the field. If instead of darting away, the fish turns from the perpendicular position, the voltage differential across the fish (from head to tail) would increase until at some point the fish loses voluntary control and enters a state of automatism. The fish might then remain in this state or, through random movement and changes in orientation, return to the zone of reactive detection or possibly begin anodic taxis. Even when all the factors noted above are the same, including orientation, observed threshold values can vary somewhat with individual specimens and even in repeated testing of the same individual, with or without adequate stress recovery periods between tests.

For specific species, size ranges, and other conditions, threshold values can be approximated for the various responses (e.g., Appendix 4 in Sternin et al. 1972, 1976–reproduced as Appendix III in this report) and used to define effective electrofishing fields. Table 2 summarizes Sternin et al.'s (1972, 1976, Appendix 4) and Kolz and Reynolds' (1989, 1990a) threshold data for twitch or reactive detection, taxis, and stun (narcosis or tetany, not distinguished). Typical voltage-gradient thresholds reported for fish in freshwater range from about 0.01 V/cm for reactive detection to 1.5 V/cm for tetany (Vibert 1963; Lamarque 1967a, 1990; Kolz and Reynolds 1989, 1990a); possibly up to 5.5 V/cm for tetany according to data summarized by Sternin et al. (1972, 1976). The comparable range for fish in seawater is 0.01 to 1.0 V/cm (Table 2). Thresholds for taxis in freshwater range from 0.1 to 1.7 V/cm (Table 2).

Voltage-gradient thresholds reported for different (or even the same) types of current (e.g., data on which Table 2 is based) are very difficult to compare. Experimental conditions are usually quite different and researchers often fail to document waveform parameters, water temperature,

Table 2. Ranges of voltage-gradient (V/cm) response thresholds summarized for various species and water conditions by Sternin et al. (1976, Appendix 4–reproduced in Appendix III of this report); also including data by Kolz and Reynolds (1989).

Current	Response		
	Twitch	Anodic Taxis	Stun
Fresh Waters, 12 to <2,000 µS/cm			
DC	0.01 - 0.34	0.11 - 1.7	0.22 - 2.6
PDC	0.05 - 0.69	0.11 - 5.4	0.05 - 5.5
AC	0.01 - 0.55	(not applicable)	0.04 - 4.8
Combined	0.01 - 0.69	0.11 - 5.4	0.04 - 5.5
Brackish and Marine Waters			
DC	0.01 - 0.04	0.06 - 0.17	0.11 - 0.42[a]
PDC	0.03 - 0.14	0.06 - 1.0	0.13 - 0.82
AC	0.02 (N = 1)	(not applicable)	0.12 (N = 1)
Combined	0.01 - 0.14	0.06 - 1.0	0.11 - 0.82

[a] A stun threshold of 5.285 V/cm was included for cod in DC in Sternin et al.'s (1976, Appendix 4) summary, but that value appears to be a typographical error; the correct value is assumed to be 0.285 V/cm.

conductivity, whether conductivity values are for ambient temperatures or standardized to 25°C (specific conductivity), or whether AC or PDC thresholds represent peak or mean values. This probably accounts for much of the variability in Table 2. Kolz and Reynolds (1989) found the range in threshold values for a particular response in all tested currents was much narrower if based on peak rather than mean intensity data (e.g., 0.13-0.19 peak V/cm versus 0.014-0.19 mean V/cm for the twitch response in DC, AC, and 50 Hz, 10-50% duty cycle PDCs when water conductivity matched effective fish conductivity, 69-119 µS/cm). As previously noted, they concluded that peak threshold values are probably more biologically significant than mean values.

Kolz and Reynolds (1989, 1990a) determined selected response thresholds for goldfish in homogeneous fields using various electrical currents and water conductivities. Based on that data, they calculated the minimum power densities required to elicit selected responses and the water conductivities at those minimum power densities. For the selected response and current type, power transfer from water to the fish was considered to be most efficient at this minimum power density, and the water conductivity at this point was considered to be the matching "effective conductivity" of the fish. For 6- to 9-cm (TL ?) goldfish, Kolz and Reynolds (1989, 1990a) found that effective conductivity varied from 69 to 160 µS/cm depending on the specific fish response and current or waveform used. Jesien and Hocutt (1990) conducted a similar investigation on power density thresholds for tetany in channel catfish (*Ictalurus punctatus*, 18-21 cm TL) under a variety of pulsed AC and PDC; they concluded that the effective conductivities were less than 100 µS/cm, the lowest water conductivity they tested. It is important to recognize that "effective fish conductivities" based on minimum power density thresholds are not the same as fish conductivities determined by other methods and that values for effective conductivities are substantially lower. For example, Monan and Engstrom (1963) reported fish conductivities of 505 to 1266 µS/cm for sockeye salmon (*Oncorhynchus nerka*), Sternin et al. (1972, 1976) reported a range of conductivities from 319 to 3571 µS/cm for a variety of freshwater fishes, and Haskell (1954) reported an approximate conductivity of 667 µS/cm (resistivity of 1,500 ohm-cm) for the flesh of brown trout.

The utility of power density thresholds and effective fish conductivities in electrofishing operations has not yet been realized and, at least for the moment, threshold data are more valuable in terms of peak-voltage gradients which can be directly measured in the water. Based on Kolz and Reynolds' (1989, 1990a) data, threshold values for reactive detection (twitch) were similar regardless of the type of current and those for narcosis (stun) were similar for AC and PDC regardless of duty cycle (Figures 11, 12). However, the threshold values for narcosis in DC were notably higher than for AC and PDC waveforms, about 60% higher in terms of voltage gradient for moderate to high conductivities. Beyond water conductivities of 200 µS/cm, and especially beyond 500 µS/cm, voltage-gradient thresholds decrease so gradually that one approximate value (for each species, size range, water temperature, and waveform) can effectively approximate the threshold at all higher levels of conductivity in freshwater. For these moderate to high water conductivities, corresponding current-density or power-density thresholds increase with water conductivity.

Zone of Reactive Detection

The outermost response zone, reactive detection (Figure 10), is the region where field intensity is just sufficient to elicit momentary twitches, shutters, or convulsions, but fish can still respond with instinctive reactions such as flight, taking cover, and possibly aggressive displays. Fish may also ignore or remain indifferent to the stimuli. In the inner, more electrically intense zones, responses are generally considered involuntary.

The zone of reactive detection is sometimes referred to as the zone of perception. But it is probable that twitches simply represent the thresholds at which fish visibly respond to "switching on" the current; fish might actually perceive the field at substantially lower field intensities and notably greater distances from the electrodes.

The zone of reactive detection is sometimes referred to as the fright zone, but the response, if any, depends very much on the species and is not necessarily one of fright. If the response is fright, it probably reflects the fish's normal behavior when startled. The response is most likely an unconditioned defensive reaction (Sternin et al. 1972, 1976) that results in many fish escaping the more effective portions of the field (Novotny and Priegel 1974). Vibert (1963), for example, noted that flatfishes "may burrow or remain on the bottom resisting the swimming response [of taxis] until narcosis or tetany take[s] over." Whether flatfish actually "resist" taxis, respond in a different, perhaps species-specific manner, or experience different electrical field parameters at the substrate interface is questionable and deserves further investigation. In some cases, the fright response attributed to an electric field might actually be a reaction to noise, motion, or related, non-electrical stimuli produced during an electrofishing operation.

At field intensities below the threshold for taxis, some biologists (e.g., Reynolds pers. commun.) suspect that fish cannot perceive a directional component to the electrical field. In this case, fish might be just as likely to dart further into the field as away from it. If fright response and consequent escape are significant, most fish captured by electrofishing were probably within the effective range (taxis, narcosis, and tetany) when the field was switched on or trapped against the shoreline, a bar, shallow riffle, or other fixed structure as the field approached. These matters should be considered when planning the approach to a sampling area and deciding where, when, how often, and how long the field should be applied.

Zones of Undirected or Inhibited Swimming and Taxis

The combined zones of undirected motion or inhibited swimming and taxis (forced swimming towards the anode, anodic taxis, electrotaxis, or oscillotaxis) represent the epileptic phase of **automatism** according to the Bozeman paradigm (Sharber pers. commun.). The threshold for taxis defines the outer limits of the effective electrofishing

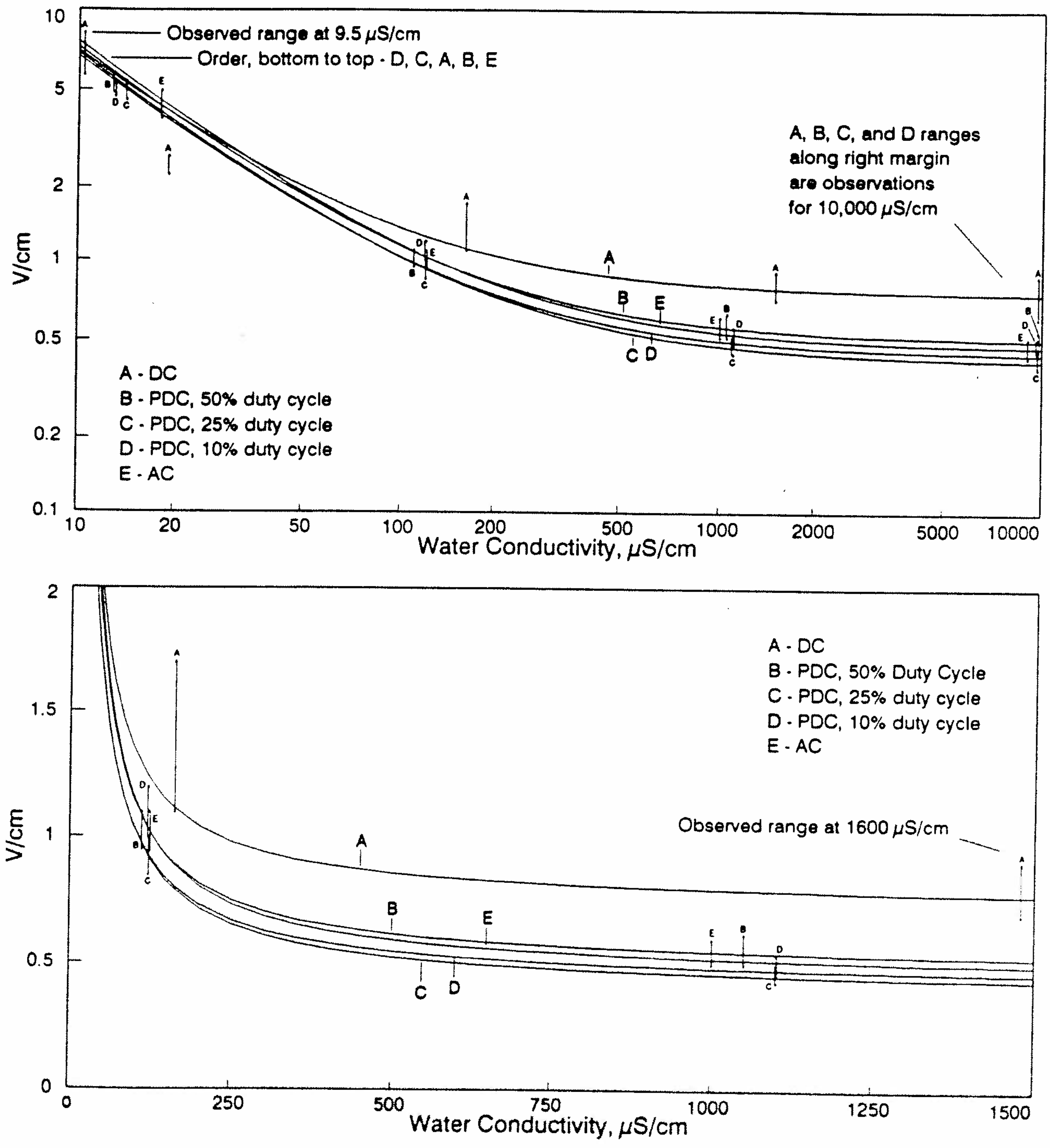

Figure 11. Peak-voltage-gradient thresholds for narcosis (stun) in 6- to 9-cm goldfish (*Carassius auratus*) in homogeneous fields of DC; 50-Hz, rectangular-wave PDC with duty cycles of 50%, 25%, and 10%; and 60-Hz sinusoidal AC. The curves are a variation of graphics presented by Kolz and Reynolds (1989). They are based on power-density minimums determined by Kolz and Reynolds for narcosis, water conductivities at those minimums ("effective" fish conductivities), and Kolz and Reynolds' equation for predicting the amount of power density (and indirectly, voltage gradient) needed in water to transfer a specific power density to fish. The latter equation is based on concepts of normalized power and load mismatch. The vertical ranges associated with the curves approximate the experimental threshold measurements presented in Kolz and Reynolds' graphs.

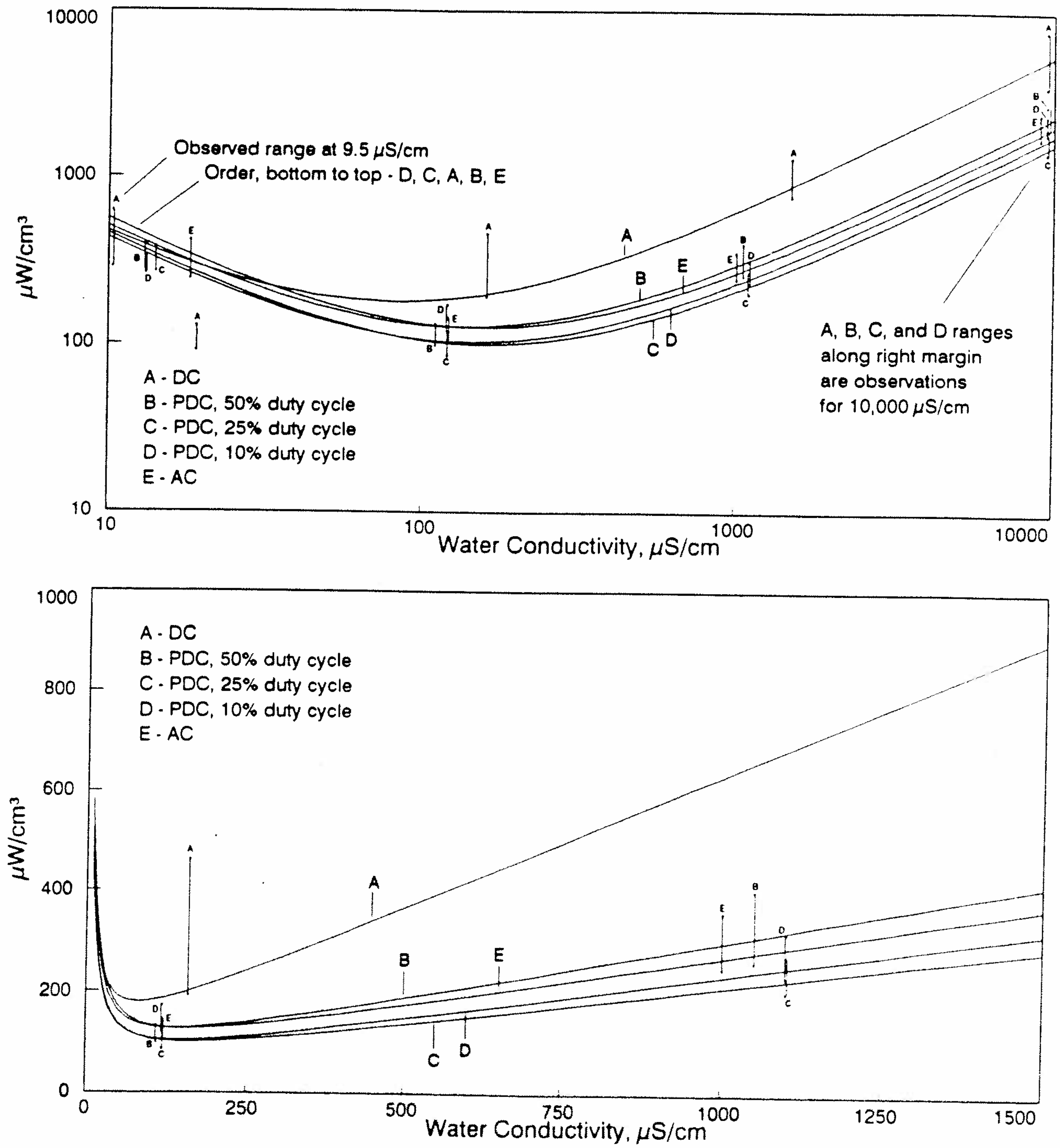

Figure 12. Peak-power-density thresholds for narcosis (stun) in 6- to 9-cm goldfish (*Carassius auratus*) in homogeneous fields of DC; 50-Hz, rectangular-wave PDC with duty cycles of 50%, 25%, and 10%; and 60-Hz sinusoidal AC. The curves are a variation of graphics presented by Kolz and Reynolds (1989). They are based on power-density minimums determined by Kolz and Reynolds for narcosis, water conductivities at those minimums ("effective" fish conductivities), and Kolz and Reynolds' equation for predicting the amount of power density needed in water to transfer a specific power density to fish. The latter equation is based on concepts of normalized power and load mismatch. The vertical ranges associated with the curves approximate the experimental threshold measurements presented in Kolz and Reynolds' graphs.

field. Without introducing a non-electric stimulus, it might be difficult to behaviorally distinguish fish that respond indifferently to an electric field below the threshold for automatism from those that exhibit undirected or inhibited motion between that threshold and the threshold for taxis. Fish in the undirected or inhibited motion state that "blunder" (Northrop 1967) into the zone of taxis, or are engulfed by that portion of a moving field, are subsequently forced to swim towards the anode until they are netted or reach the zone of narcosis. Some fish in taxis have enough momentum to carry them through the zone of narcosis into the zone of tetany.

Haskell et al. (1954) suggested that due to continually changing orientation of a fish's body, especially in a moving field, taxis towards the anode in DC and PDC is a composite of voluntary swimming movements caused by the central nervous system, involuntary bends of the body toward the anode (especially upon initial circuit closure in DC and with each pulse in PDC), and anesthesia (presumably narcosis only). They also observed that the response of involuntary bends toward the anode is strongest when fish are perpendicular to the lines of current, whereas the anesthetic response is greatest when fish are parallel to the lines of current.

Lamarque (1990) suggested that anodic taxis under PDC is distinctly different from that under DC. Haskell et al. (1954) concluded that DC "modifies the normal swimming motion and guides the fish toward positive pole" whereas PDC causes an "involuntary . . . turn toward the positive pole and forward motion at each circuit closure." Haskell et al (1954) and Lamarque (1990) also noted that motion resulting from PDC required a lower voltage threshold and was more pronounced than that from DC. Some biologists (e.g., Fredenberg pers. commun.) have observed that taxis can be so powerful in some PDC currents that fish sometimes appeared to swim rapidly by and beyond the anode without succumbing to narcosis or tetany. Some of these fish ultimately circled back towards the anode. In AC, taxis cannot be sustained towards either electrode because the current continually reverses direction and the fish ultimately aligns itself perpendicular to the lines of current in a "swimming" response referred to as transverse oscillotaxis.

Zones of Narcosis and Tetany

Narcosis and tetany represent two distinct forms of stunned immobility (Vibert 1963). The zone of narcosis or **petit mal** (Sharber pers. commun.) is characterized by a loss of equilibrium, limp or relaxed muscles, and reduced respiration. The zone of tetany or **grand mal** (Sharber pers. commun.) is represented by a partial to full state of sustained muscle contraction. In full tetany, fish are rigid and respiratory movements cease. Fish in the outermost, lower intensity, portions of the zone of tetany sometimes exhibit a very confined and rapid swimming motion, usually while lying on their sides or backs. This initial phase of tetany or grand mal was described by Biarritz researchers as pseudo-forced or second swimming towards the anode. When fish in states of taxis, narcosis, or even the beginning of tetany are removed from the electric field (by netting, switching the field off, or moving it away from the fish), they usually recover immediately and behave in a relatively normal manner. However, fully tetanized fish or those in the zone of tetany for excessive periods of time may require several minutes to recover normal muscle response, respiratory movements, and equilibrium. Full physiological recovery takes much longer. Some fish never recover and die.

The terms narcosis and tetany are often confused and used interchangeably. In some cases, failure to distinguish these terms is due to difficulty in identifying the initial states of partial tetany. For example, Northrop (1962, 1967) properly noted that during narcosis the fish is limp, but he also suggested that narcosis might involve anoxia due to paralysis of the respiratory musculature, or even temporary cardiac arrest, conditions typically attributed to tetany. The terms "stun" or "stunned" are used herein to refer to immobilization in either state when the distinction is unnecessary or the specific state is undefined. The term "shock" is sometimes used as a synonym for stun (Sternin et al. 1976); but it is also used frequently in reference to electrofishing in general, any response to an electrical stimulus, and the electrical stimulus producing a response, especially a sudden, violent contraction of muscles.

Lamarque (1990, 1976a) observed that in a DC field just sufficient for narcosis, a fish facing the anode can remain narcotized for several hours without any trouble. Like electrofishing, fishery biologists have found immobilization by controlled electrical narcosis to be a useful tool when tagging and gathering specimen-specific data on fish, especially large fish (Hartley 1967; Gunstrom and Bethers 1985; Orsi and Short 1987). The technique is often referred to as anesthesia, but Hartley (1967) emphasized that although the fish is temporarily paralyzed and appears unconscious, we do not know whether it is insensitive to touch or pain. For these purposes, fish are usually subjected to a relatively homogeneous electric field in a small chamber where voltage gradients are easily controlled. Smooth DC is preferred to minimize the risk of tetany and because the operator can handle the fish in the water without feeling the current himself, unless he has cuts on his hands (Hartley 1967). According to Kynard and Lonsdale (1975) and Hartley (1967), fish can be instantly immobilized by initially applying twice the minimum voltage subsequently needed to maintain narcosis. These voltage levels are arrived at experimentally or through experience and depend primarily on water conductivity, species, and size of the fish. Unless fish are physically restrained, the higher initial field intensity is probably necessary because many fish will not be aligned parallel to the lines of current when the field is switched on. Another method to "anesthetize" fish is to place them in direct contact with the electrodes, usually on a table with the anode contacting the head and the cathode contacting the body (Kolz, M. L., 1989). As long as the body of the fish conducts the proper amount of current, the fish is immobilized; when the circuit is broken the fish recovers instantly unless it was maintained under narcosis more than a couple hours. Kynard and Lonsdale (1975) found that yearling rainbow trout held under narcosis for several hours required half a day to resume normal swimming and feeding behavior, but growth and phototropic response over the next 25 d were unaffected. They also documented a decrease in ventilation rate, up to 52%, for yearlings held under narcosis for 4 h.

Comparison of Currents for Electrofishing

In DC or PDC fields, the effective range for capture begins with the zone of taxis; in AC fields, for which significant taxis towards an electrode is not possible, the effective range usually begins with the zone of narcosis. Many reviews of electrofishing conclude that at comparable average power output, AC has a greater effective range than either DC or PDC, but fish are stunned almost immediately without first producing significant taxis. Lack of taxis toward a near-surface electrode can make netting fish difficult, especially in deeper, more turbid waters. In most electrofishing operations, taxis and narcosis are the responses to be sought and optimized, whereas tetany is considered dangerous and to be minimized or avoided. As noted earlier, the zone of tetany can be controlled to some degree by careful selection of output power and the size, shape, and configuration of the electrodes (Chmielewski et al. 1973; Novotny and Priegel 1971, 1974; Novotny 1990).

Although Haskell (1950) suggested that DC is more dangerous to man than AC, most electrofishing authorities consider AC, with it's relatively large zone of tetany, more dangerous to fish and perhaps the electrofishing team than either DC or PDC (e.g., Hauck 1949; Taylor et al. 1957; Lamarque 1967a, 1990; Northrop 1967; Vibert 1967b; Vincent 1971; Novotny and Priegel 1974; Reynolds 1983). Lamarque (1967a) specifically observed that AC (and PDC) can provoke violent tetanus. Excessive exposure to tetanizing currents can result in severe stress, unrecoverable fatigue, or respiratory failure (see below). Still, Hudy (1985), Schneider (1992), and other researchers maintain that AC can be effectively used without significant harm to the populations being studied. Schneider (1992) noted that some state agencies continue to make extensive use of AC electrofishing. If AC can be used without significant harm to the fish, the substantial zones of narcosis and tetany in AC might actually be desired to improve capture efficiency under certain conditions—usually in shallow, clear, slow-moving water where fish can be easily netted and rapidly removed from the electrical field. However, AC is probably best reserved for situations in which fish are being permanently removed and injury or survival is not a serious concern (McCrimmom and Berst 1963).

In contrast to AC, the effective range of DC is much smaller, not only because the field is less intense at the same average power output, but because thresholds for comparable responses are notably higher. Despite these limitations, DC has the considerable advantage of good anodic taxis with most species of fish and is considered the least damaging current. Lamarque (1990) noted that DC generated by full-wave rectification of three-phase AC (600 Hz) has less ripple (4%) and a correspondingly less tetanizing effect on fish than DC which is only half-wave rectified (300 Hz, 17% ripple).

The effective size of PDC fields and their effects on fish are generally considered intermediate to those of AC and DC (Lamarque 1990). Vincent (1971) and others report that PDC not only produces larger and more intense fields than DC at the same average power output, but induces DC-like responses at lower thresholds. It thereby creates still larger effective zones or allows use of lower power output to produce fields with effective zones of the same size. Vincent (1971) further suggested that because the zones of narcosis and tetany, as well as taxis, are larger in PDC than DC fields, fish might be more difficult to net and more susceptible to tetany and tissue damage. Stunned fish are usually easier to net than rapidly moving fish (Meyer pers. commun.), but if fish are stunned beyond the reach of the netters, they may be missed and escape capture. Chmielewski et al. (1973) noted that fish stunned while taking cover are less likely to be captured and those initially stunned in flowing water may be washed away before they can be netted.

Haskell et al. (1954) tested 8- to 18-cm brown trout in rectangular-wave PDC at various frequencies at and below 60 Hz. Using a shallow heterogenous field in a wooden tub, he observed no significant reactions until the frequency was reduced to about 15 Hz and reported increasingly stronger responses as the frequency was further reduced to 1 or 2 Hz. Using a homogeneous field in a narrow trough, Kolz and Reynolds (1989) also failed to observe taxis among 6- to 9-cm goldfish subjected to 50-Hz PDC, but they did observe twitch and stun responses. Contrary to these reports and without an explanation for the apparently contradictory results, more recent observations and in-field use of PDC systems (often operated at 30 to 60 Hz) suggest that taxis in PDC is usually not only evident but much better at frequencies greater than 15 Hz (Sharber pers. commun; Sharber et al. unpubl. ms. 1989, unpubl. ms. 1991). Vincent (1971) stated that with frequencies at or below 50 Hz, PDC is as effective or more effective than DC in producing anodic taxis. Northrop (1962, 1967) found that rectangular-wave PDC was most effective at inducing taxis in 20- to 25-cm brown trout when operated at 33 Hz with a 67% duty cycle (20-ms pulse width). Reynolds et al. (1992) reported capturing three northern pike with 60-Hz PDC for every one caught with DC or 30-Hz PDC.

But Northrop (1962, 1967) also found, in the same set of experiments, that fish were immediately stunned and showed no significant electrotaxic behavior when subjected to a PDC of 100 Hz with a 50% duty cycle (5-ms pulse width). In experiments with 20-cm rainbow trout in homogeneous fields and again in apparent contradiction to the above observations, Taylor et al. (1957) not only observed taxis at frequencies as high as 120 Hz, but reported lower thresholds for strong taxis at 48 to 120 Hz (0.33-0.25 peak V/cm) than at 36, 24, and 12 Hz (0.48, 0.78, and 0.87 peak V/cm, respectively). Taylor et al. (1957) also observed a similar inverse relationship between frequency and voltage-gradient thresholds for narcosis. In heterogeneous fields of similar intensity, lower voltage-gradient thresholds result in larger effective zones for the pertinent responses. Speculating without detailed knowledge of Northrop's experimental procedures, perhaps during his observations for 100-Hz PDC the effective zones for both taxis and narcosis were so large or distant that he only observed and netted narcotized fish (i.e., taxis may have occurred beyond his range for netting fish). Based on experiments also with 20-cm trout (brown or rainbow), Lamarque (1976) concluded that at 18°C the optimum PDC frequency for taxis was around 100 Hz (3-ms pulse width), but noted that lower frequencies might be better for electrofishing since fish near the electrode were also more subject to tetany at this higher frequency.

Vincent (1971) concluded that DC is the best current for capture efficiency in rivers which have brushy bank cover or where turbidity is high, whereas PDC is best for large open rivers with less bank cover and clearer water, or for waters which are too conductive for effective use of DC. He also reported that a hybrid DC-PDC current, "half-pulsed direct current", has qualities intermediate to DC and PDC.

ADVERSE IMPACTS

Possible detrimental effects of electrofishing on individual fish include cardiac or respiratory failure, injury, stress, and (or) fatigue. Mortality can be immediate or delayed. Slowed or inhibited behavioral responses can make smaller fishes more susceptible to predation. Fish that survive despite electrofishing injury or other adverse impacts, may suffer short-term, long-term, or lifetime handicaps that affect their behavior, health, growth, or reproduction. Significant numbers of surviving but adversely affected fish may ultimately impact community ecology, population size, quality of the fishery resource, and management strategies. Table 3 and Appendix IV (appendix table from Sternin et al. 1972, 1976) summarize adverse effects reported in published literature, agency reports, and personal communications.

In most cases, the adverse effects of electrofishing can be traced to one of two causes, excessive exposure in the zone of tetany and aspects of the electrical field that result in sudden, powerful contractions of the body musculature. The field characteristics and specific mechanisms responsible for these convulsions have not been conclusively identified, but field intensities for the response apparently extend well below those for tetany. Injuries due to such seizures are generally classified as spinal injuries but may include damage to tissues or organs not associated with the vertebral column or notochord (in cartilaginous fishes).

Effects Other Than Spinal and Related Injuries

Among non-spinal injuries, the most extreme would likely be electrocution when fish are sufficiently exposed to very high voltage gradients. In humans and other mammals, fibrillation of the heart and death by cardiac arrest are common results of exposure to strong electric currents, but electrofishing mortalities are usually rare and such effects in fish are inadequately documented in the published literature. Northrop (1962, 1967) suggested that "temporary" cardiac arrest might occur in electrically narcotized (tetanized?) fish, whereas Kolz and Reynolds (1990b) stated that cardiac arrest is seldom a factor in fish mortality. But neither evidence nor references were provided to support either statement.

Based on an experiment with tetanizing DC on a rainbow trout, Taylor et al. (1957) reported that although they observed an arrhythmia (an extra beat followed by skipped beats) when the current was initially applied, normal heart beats quickly resumed even as the current continued to be applied. They concluded, based on this one experiment, that the heart was not severely affected by electrofishing currents. However, the kymogram that accompanied their report indicates that skipped beats continued after the initial current was momentarily interrupted and that normal beats resumed after current was reestablished. The events in Taylor et al.'s (1957) experiment are certainly open to alternative interpretations, none of which can be effectively supported by only one kymogram. Perhaps cardiac arrest had indeed occurred and the next impulse was required to start the heart again. In any case, the effects of an electric field on the heart might be quite different for PDC or AC.

In experiments by Schreck et al. (1976) recovery of normal heart activity took much longer. Their fish also exhibited irregular cardiac activity immediately after being shocked (tetanized?) with DC but required 4 to 5 min to return to normal. In two fish that were shocked for 45 and 60 s and failed to resume respiration, heart activity initially appeared to recover then decreased in frequency and amplitude and finally ceased in about 15 to 25 min.

The visceral organs of fish may also be affected by electric fields. Shparkovskij and Vataev (1985) stimulated the brain of Atlantic cod (*Gadus morhua*) using rectangular-wave PDC of 0.1 to 0.5 mA and a burst (?) frequency of 300 Hz. When the lateral areas of end-brain and mid-brain were stimulated, peristalsis of the stomach and gut was inhibited. When the rostral cerebellum was stimulated, muscle contraction of the digestive tract was accelerated. Marriott (1973) described two ripe female pink salmon (*Oncorhynchus gorbuscha*) that had been electrocuted with 110-V, 60-Hz AC as having severely ruptured internal organs. However, Taylor et al. (1957) compared sections of various organs and tissues from an electrocuted rainbow trout with those from an untreated trout and reported no abnormalities.

Table 3. Summary of electrofishing mortality and injuries as reported in published literature, agency documents, and (with permission) unpublished manuscripts and personal communications. Within species, records are ordered by current type and frequency.[a,b]

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality: Short-term	Mortality: Long-term	Spinal Injuries: Brands	Spinal Injuries: Spine/Vertebrae Extern.	Spinal Injuries: Spine/Vertebrae Intern.	Spinal Injuries: Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
Acipenseridae																		
***Scaphirhynchus platorynchus*, shovelnose sturgeon**																		
≤91 TL	5						0%	0%		Rivers	600	11	*	PDC	60	8 ?	Rect.	Fredenberg 1992
≤77 TL	3						0%	0%		Rivers	600	11	*	PDC-CPS	240/15	1.6/10	Rect.	Fredenberg 1992
Polyodontidae																		
***Polyodon spathula*, paddlefish**																		
			high [c]				high [c]			Rivers			*	PDC				Pfeifer pc
Cyprinidae																		
***Campostoma oligolepis*, largescale stoneroller**																		
	few		≥0% [d]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
***Carassius auratus*, goldfish**																		
6-9			0 [d]		0 [d]	0 [d]			0 [d]	Lab. trough	18-10000	20	=	AC	60		Sine	Kolz & Reynolds 1989
6-9			0 [d]		0 [d]	0 [d]			0 [d]	Lab. trough	9.5-10000	20	=	DC				Kolz & Reynolds 1989
6-9			0 [d]		0 [d]	0 [d]			0 [d]	Lab. trough	13-10000	20	=	PDC	50	10	Rect.	Kolz & Reynolds 1989
6-9			0 [d]		0 [d]	0 [d]			0 [d]	Lab. trough	14-10000	20	=	PDC	50	5	Rect.	Kolz & Reynolds 1989
6-9			0 [d]		0 [d]	0 [d]			0 [d]	Lab. trough	13-9700	20	=	PDC	50	2	Rect.	Kolz & Reynolds 1989
***Clinostomus funduloides*, rosyside dace**																		
	few		≥0% [d]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
***Cyprinella lutrensis*, red shiner**																		
	*				0	0				Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
***Cyprinus carpio*, common carp**																		
			1 [f]			1 [f]				Rivers, CRB			*	PDC				Kinsolving pc
			0		0	0				Rivers, CRB	500-800	15-25	*	PDC				Valdez pc
	*				0	0	0 ?			Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
***Gila cypha*, humpback chub**																		
			0			0				Rivers, CRB			*					Pfeifer pc
			~0.01%		X					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc
					X [e]				X [e]	Rivers etc,CRB			*	PDC				Trammell pc

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality		Spinal Injuries				Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
			Short-term	Long-term	Brands	Spine/Vertebrae Extern.	Spine/Vertebrae Intern.	Intern. Hemor.										
					X [g]				X [g]	Rivers etc,CRB			*	PDC-CPS	240/15	1.6/10	Rect.	Trammell pc
juv.-ad.			0		0					Rivers etc,CRB	250-3500		*	PDC,DC				Burdick pc
Gila elegans, **bonytail**																		
			~0.01%		0					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc
Gila robusta, **roundtail chub**																		
					0					Rivers, CRB	600-1000	15-20	*	PDC,DC?				Buntjer pc
			0		0	0				Rivers, CRB	500-800	15-25	*	PDC				Valdez pc
	*				0	0				Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
Luxilus coccogenis, **warpaint shiner**																		
	few		≥0% [d]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
Luxilus cornutus, **common shiner**																		
5-9 TL	>16	X [m]	X [m]							Shocking tank			=	DC				Adams et al. 1972
Notemigonus crysoleucas, **golden shiner**																		
5-10 TL	7		0% [n]							Lakes	>66, <520	13-14	*	AC	180 [n]		[n]	Schneider 1992
Notropis leuciodus, **Tennessee shiner**																		
	few		≥0% [d]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
Pimephales promelas, **fathead minnow**																		
	*				0	0				Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
Plagopterus argentissimus, **woundfin**																		
	*				0	0				Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
Ptychocheilus lucius, **Colorado squawfish**																		
			0			0				Rivers, CRB			*					Pfeifer pc
juv.-ad.			0	low [k]	1 [h]					Rivers etc,CRB	250-3500		*	PDC&DC				Burdick pc
					0					Rivers, CRB	600-1000	15-20	*	PDC,DC?				Buntjer pc
					X [i]					Rivers, CRB			*	PDC?				Hawkins pc
juv.-ad.			1 [j]						1 [j]	Rivers etc,CRB			*	PDC			Rect.	Emblad pc
10-90 TL		X [h]	0	low [h]	1 [h]					Rivers, CRB	200-2000	0-25	*	PDC				McAda pc
			~0.01%		X					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc
adults	20		0	5%? [l]	0	0				Rivers, CRB	300-1500	5-15	*	PDC	30,40	20		Valdez pc

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality		Spinal Injuries				Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
			Short-term	Long-term	Brands	Spine/Vertebrae Extern.	Spine/Vertebrae Intern.	Intern. Hemor.										
***Rhinichthys cataractae*, longnose dace**																		
	few		≥0% [d]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
***Rhinichthys osculus*, speckled dace**																		
	•				0	0				Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
***Semotilus atromaculatus*, creek chub**																		
	few		≥0% [d]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
Catostomidae																		
***Catostomus commersoni*, white sucker**																		
					X					Rivers, CRB			*	PDC?				Hawkins pc
			0		0	0				Rivers, CRB	500-800	15-25	*	PDC				Valdez pc
	•				0	0	0 ?			Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
***Catostomus discobolus*, bluehead sucker**																		
					0					Rivers, CRB	600-1000	15-20	*	PDC,DC?				Buntjer pc
					X					Rivers, CRB			*	PDC?				Hawkins pc
			~0.01%		X					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc
			0		0	0				Rivers, CRB	500-800	15-25	*	PDC				Valdez pc
	•				0	0	0 ?			Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
***Catostomus latipinnis*, flannelmouth sucker**																		
			~0.01%		X					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc
			0		0	0				Rivers, CRB	500-800	15-25	*	PDC				Valdez pc
	•				0	0	0 ?			Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
					0					Rivers, CRB	600-1000	15-20	*	PDC,DC?				Buntjer pc
					X					Rivers, CRB			*	PDC?				Hawkins pc
***Erimyzon sucetta*, lake chubsucker**																		
5-25 TL	41		0% [da]							Lakes	>66, <520	13-14	*	AC	180 [da]		[da]	Schneider 1992
***Hypentelium nigricans*, northern hog sucker**																		
	few		≥0% [d]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
***Xyrauchen texanus*, razorback sucker**																		
	~50		0		0					Rivers, CRB	200-2000	0-25	*	PDC				McAda pc
			~0.01%		0					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil. Recov.	Mortality Short-term	Mortality Long-term	Brands	Spinal Injuries Spine/Vertebrae Extern.	Spinal Injuries Spine/Vertebrae Intern.	Spinal Injuries Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
adults	20		0	10%?	0	0				Rivers, CRB	300-1500	5-15	•	PDC	30,40	20		Valdez pc
juv.-ad.			0		0					Rivers etc,CRB	250-3500		•	PDC,DC				Burdick pc
Ictaluridae																		
***Ictalurus punctatus*, channel catfish**																		
adults ?	10		0%				≥60%			Hatch. ponds	167		•	AC	180			Spencer 1966 &1967
		X			0					Rivers, CRB	600-1000	15-20	•	PDC,DC?				Buntjer pc
		X								Rivers, CRB			•	PDC?				Hawkins pc
	•				0	0				Rivers etc,CRB	<50->5000	>0->30	•	PDC	60			Krueger pc
Esocidae																		
***Esox lucius*, northern pike**																		
juv.-ad.			0		0					Streams	25-200	5-15	•	PDC?				Valdez pc
36-74 FL	60						5%			Shocking tank	109-132	11-16	=	PDC	30	16.7		Roach 1992.
52-68 FL	27							0%		Shocking tank	158-188	11-15	=	PDC	30	16.7		Roach 1992.
36-74 FL	60						10%			Shocking tank	109-132	11-16	=	PDC	30	16.7		Roach 1992.
40->80FL	32		0.2%				16%	19%		Rivers	210		•	PDC	60	8.3		Holmes et al. 1990
	•				0	0	0 ?			Rivers etc,CRB	<50->5000	>0->30	•	PDC	60			Krueger pc
52-68 FL	27						>14%	15%		Shocking tank	158-188	11-15	=	PDC	60	8.3		Roach 1992.
36-74 FL	60						8%			Shocking tank	109-132	11-16	=	PDC	60	8.3		Roach 1992.
36-74 FL	60						12%			Shocking tank	109-132	11-16	=	PDC	60	8.3		Roach 1992.
38-77 FL	140/ 174			0%			>29%			Shocking tank	1017-1090	10-13	=	PDC	120	4.2		Roach 1992.
Salmonidae (unspecified species)																		
juv.-ad.			0				most		X	Rivers etc,CRB	250-3500		•	PDC,DC				Burdick pc
<46 TL						X				Rivers, streams	<100		•	PDC				Gowan pc
***Coregonus pidschian*, humpback whitefish**																		
33-45	278/60		5%				3%	7%		Rivers	80-88	10-11	•	PDC	80	5		Holmes et al. 1990
***Coregonus sardinella*, least cisco**																		
28-38	106/83		15%				5%		30%	Rivers	80-88	10-11	•	PDC	80	5		Holmes et al. 1990
***Oncorhynchus clarki*, cutthroat trout**																		
			0.5%		10%					Streams	<100	5-15	•	DC?				Valdez pc

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality: Short-term	Mortality: Long-term	Spinal Injuries: Brands	Spinal Injuries: Spine/Vertebrae Extern.	Spinal Injuries: Spine/Vertebrae Intern.	Spinal Injuries: Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
yoy-ad					X					Rivers, CRB	<25?-1000	0-19	•	PDC				Buntjer pc
″					<1%					Streams	10-100		•	DC?				Valdez pc
***Oncorhynchus gorbuscha*, pink salmon**																		
juv.-ad.		high		low	high					Streams		5-15	•	AC	60			Valdez pc
***Oncorhynchus kisutch*, coho salmon**																		
7 TL	107		78%							Lab shock tank		17	=	PDC	8	40	Rect.	Collins et al. 1954
7 TL	107		0%							Lab shock tank		17	=	PDC	8	40	Rect.	Collins et al. 1954
yoy, 6-10	197		3%							Hatch. raceway	67-100	17	•	PDC	15	8.3	½ Sine	Pugh 1962
yoy, 6-10	207		2%							Hatch. raceway	200-1000	17	•	PDC	15	8.3	½ Sine	Pugh 1962
yoy, 6-10	195		9%							Hatch. raceway	67-100	17	•	PDC	15	8.3	Rect.	Pugh 1962
yoy, 6-10	206		4%							Hatch. raceway	200-1000	17	•	PDC	15	8.3	Rect.	Pugh 1962
yoy, 6-10	194		7%							Hatch. raceway	67-100	17	•	PDC	30	8.3	½ Sine	Pugh 1962
yoy, 6-10	207		5%							Hatch. raceway	200-1000	17	•	PDC	30	8.3	½ Sine	Pugh 1962
yoy, 6-10	194		18%							Hatch. raceway	67-100	17	•	PDC	30	8.3	Rect.	Pugh 1962
yoy, 6-10	194		6%							Hatch. raceway	200-1000	17	•	PDC	30	8.3	Rect.	Pugh 1962
***Oncorhynchus mykiss*, rainbow trout**																		
>40 FL	22						50%			Rivers	>50	>7	•					Reynolds et al. 1988
>40 FL							X			Rivers,net-pens			•					Reynolds et al. 1988
~19 TL	48		4%							Hatch. raceway	306 @25C		•	AC				Pratt 1955
Large	503	X	26%		X	X	X	X	X	Canal		14-21	•	AC	60		Sine	Hauck 1949
11-27 TL	50						0%			Shocking tank	475-550	11-13	•	AC	60		Sine	McCrimmon & ... '71
4-36 SL	46		4%							Shocking tank	1494 ?	16-18	=	AC	60			Taylor et al. 1957
16-26	375		3%		2%					Hatch. raceway	10	6	•	AC,350V	300			Hudy 1985
16-26	375		2%		2%					Hatch. raceway	10	6	•	AC,700V	300			Hudy 1985
16-26	375		1%		1%					Hatch. raceway	10	6	•	AC,760V	250-300			Hudy 1985
4-36 SL	91		0%							Shocking tank	1494 ?	16-18	=	DC				Taylor et al. 1957
Large				~35%			<18%			Shocking tank			=	DC				Reynolds et al. 1992
~19 TL	48		2%							Hatch. raceway	306 @25C		•	DC				Pratt 1955
~20 TL	16		13%			6%				Hatchery		6-10	•	DC				Bouch and Ball 1966
~12	60		0-13%							Lab shock tank	<450	13-21	=	DC				Kynard & Lonsdale '75

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality: Short-term	Mortality: Long-term	Brands	Spinal Injuries: Spine/Vertebrae Extern.	Spinal Injuries: Spine/Vertebrae Intern.	Spinal Injuries: Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
~14-48FL	32/23 [cl]		0% [cl]		3% [cl]		4% [cl]	4% [cl]		Hatch. raceway	80	9-11	*	DC,300V				McMichael &... um'91
~14-48FL	25/29 [cl]		~3% [cl]		8% [cl]		14% [cl]	17% [cl]		Hatch. raceway	80	9-11	*	DC,400V				McMichael &... um'91
30-43 TL	56						13% [bk,bl]	25% [bk,bl]		Rivers	300-320	6-12	*	DC				Fredenberg 1992
25-47 TL	21						5% [bk]	0% [bk]		Rivers	177	10-15	*	DC				Fredenberg 1992
27-54 TL	28						18% [bk,bm]	11% [bk,bm]		Rivers	540	18	*	DC				Fredenberg 1992
33-43 TL	47						30% [bk,bw]	72% [bk,bw]		Rivers	300-320	6-12	*	Hybrid [bx]	60	<8 ?	½ Sine	Fredenberg 1992
~20-55TL	152				26% [bn]		63% [bn]			Rivers	540-900	7-18	*	Various [bn]				Fredenberg 1992
26-43 TL	50 [cc]		≤8% [cc]				60%			Rivers	299		*	Various [cd]				Meyer & Miller 1990[ce]
yoy-ad					X [v]					Rivers, CRB	<25?-1000	0-19	*	PDC				Buntjer pc
20-68 FL	72/32 [c]		14% [cm]		24%		75% [cb]	75% [cb]		Rivers	70	6.3	*	PDC				Holmes et al. 1990
4-36 SL	1641		0.3%							Shocking tank	1494 ?	16-18	=	PDC		33% [bg]		Taylor et al. 1957
					X ? [g]				X ? [g]	Rivers etc,CRB			*	PDC				Trammell pc
			0		X	0				Rivers, CRB	500-800	15-25	*	PDC				Valdez pc
			~0.01%		X					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc
juv, 19TL	825			7%? [bi]						Shocking tank	143-172	11-13	= [bi]	PDC	5	60	Rect? [bi]	Maxfield et al. 1971
yoy,5TL	954 [bj]			10%? [bj]						Shocking tank	114-132	9-11	= [bj]	PDC	8	40	Rect? [bj]	Maxfield et al. 1971
>30 TL	38						3%			Rivers, CRB	600-800	9-11	*	PDC	15	5	Rect.	Sharber et al. um 1991
adults	40						3% [cn]			Lab. trough	572	12	=	PDC	15	5	Rect.	Sharber et al. um 1991
>30 TL	38						24%			Rivers, CRB	600-800	9-11	*	PDC	30	4	Rect.	Sharber et al. um 1991
~14-48FL	27/23 [cl]		~0% [cl]		4% [cl]		22% [cl]	35% [cl]		Hatch. raceway	80	9-11	*	PDC	30			McMichael &... um'91
14-40 TL	34 [ch]						35% [ch]			Rivers	340-350	7-8	*	PDC	40	5	Rect.?	WY Game Fish '91 [cj]
16-31 TL	11 [ci]						0% [ci]			Rivers	340-350	7-8	*	PDC	40	5	Rect.?	WY Game Fish '91 [cj]
14-32	240/4 [da]		1-3% [da]				0% [da]			River, scap net	<250?	11-12	*	PDC	45	1.6	Rect.	Shetter et al. 1969
28-61	75		0% [db]							River, scap net	<250?	11-12	*	PDC	45	1.6	Rect.	Shetter et al. 1969
Large				~35% [ck]			<20-60%			Shocking tank			=	PDC	20-60			Reynolds et al. 1992
30-56 TL	99						44%	[cd]		Rivers, CRB	600-800	9-11	*	PDC	60	4.2	Expo.	Sharber & Carothers'88
30-56 TL	55						67%	[cd]		Rivers, CRB	600-800	9-11	*	PDC	60	4.2	¼ Sine	Sharber & Carothers'88
31-43 TL	45						42% [bk,bx]	69% [bk,bx]		Rivers	300-320	6-12	*	PDC	60	8	½ Sine	Fredenberg 1992
24-45 TL	39 [bn]						59% [bk,bn]	87% [bk,bn]		Rivers	33-55	4-6	*	PDC	60	8	½ Sine	Fredenberg 1992
24-48 TL	23						52% [bk,bv]	61% [bk,bv]		Rivers	150-175	13	*	PDC	60	8	½ Sine	Fredenberg 1992
23-53 TL	54						50% [bk,bm]	59% [bk,bm]		Rivers	880-900	7-11	*	PDC ? [bm]	60 ? [bm]	8 ? [bm]	Rect? [bm]	Fredenberg 1992

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality		Brands	Spinal Injuries			Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
			Short-term	Long-term		Spine/Vertebrae		Intern. Hemor.										
						Extern.	Intern.											
adults? [cn]			≤0.5%							Streams	<100-200	<10-15	*	PDC? [co]	60? [co]	<8? [co]	½Sine?	Nehring 1991
adults? [cn]			<1-5%			<1-5%				Streams	<100-200	<10-15	*	PDC? [cp]	60? [cp]	<8? [cp]	½Sine?	Nehring 1991
30-56 TL	55						44%	[ad]		Rivers, CRB	600-800	9-11	*	PDC	60	4.2	Rect.	Sharber & Carothers'88
>30 TL	60						43%			Rivers, CRB	600-800	9-11	*	PDC	60	4.2	Rect.	Sharber et al. um 1991
>30 TL	61						43%			Rivers, CRB	600-800	9-11	*	PDC	60	4.2	Rect.	Sharber et al. um 1991
>30 TL	23						65%			Rivers, CRB	600-800	9-11	*	PDC	60	4.2	Rect.	Sharber et al. um 1991
adults	30						18%			Hatch. raceway				PDC	60	4.2	Rect.	Sharber pc
adults							33% [ae]			Lab. trough [ae]	572 ?	12 ?	=	PDC	60	4	Rect.	Sharber pc
adults							3% [af]			Lab. trough [af]	572 ?	12 ?	=	PDC	60	4	Rect.	Sharber pc
30-36 TL	9		78%? [cf]				78%			Rivers	600-616		*	PDC	60	7	Rect.?	Meyer & Miller 1990
41-52 TL	30						13% [bk]	57% [bk]		Streams	195	6	*	PDC	60	8?	Rect.	Fredenberg 1992
30-43 TL	42[bo]						67%[bk,bo]	91%[bk,bo]		Rivers	33-34	4-6	*	PDC	60	8?	Rect.	Fredenberg 1992
26-53 TL	46						68%[bk,bp]	59%[bk,bp]		Rivers	880-900	7-11	*	PDC	60	8?	Rect.	Fredenberg 1992
19-20 TL	102			2%? [bk]	39% [bk]					Hatch. raceway	242 @ 25C		*	PDC	60			Horak & Klein 1967
~35			0			1 [cc]				Rivers, CRB			*	PDC	60			Kinsolving pc
adults?	•				50%	0 ?	50% ?			Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
~14-48FL	26/17 [cl]		~0% [cl]		58% [cl]		35% [cl]	53% [cl]		Hatch. raceway	80	9-11	*	PDC	90			McMichael &... um'91
13-26 TL	30						0% [cm]			Shocking tank	500-550	11	*	PDC	120	8	½ sine	McCrimmon & ... '71
28-37 TL	44						5-29%[bk]			Hatchery	238	4	*	PDC	250		Rect.	Fredenberg 1992
>30 TL	61						61%			Rivers, CRB	600-800	9-11	*	PDC	512	0.2	Rect.	Sharber et al. um 1991
>30 TL	43						9%			Rivers, CRB	600-800	9-11	*	PDC-CPS	240/15	1.6/10	Rect.	Sharber et al. um 1991
>30 TL	41						7%			Rivers, CRB	600-800	9-11	*	PDC-CPS	240/15	1.6/10	Rect.	Sharber et al. um 1991
adults	30						6%			Hatch. raceway				PDC-CPS	240/15	1.6/10	Rect.	Sharber pc
30-41 TL	4		[cg]				50%			Rivers	600-616		*	PDC-CPS	240/15	1.6/10	Rect.	Meyer & Miller 1990
16-39 TL	51 [cj]						12%			Rivers	340-350	7-8	*	PDC-CPS	240/15	1.6/10	Rect.	WY Game Fish '91 [cj]
40-50 TL	30						10% [bk]	77% [bk]		Streams	195	6	*	PDC-CPS	240/15	1.6/10	Rect.	Fredenberg 1992
30-43 TL	12 [bq]						17% [bk]	25% [bk]		Rivers	35-55	4-6	*	PDC-CPS	240/15	1.6/10	Rect.	Fredenberg 1992
20-55 TL	44						43%[bk,br]	34%[bk,br]		Rivers	540	18	*	PDC-CPS	240/15	1.6/10	Rect.	Fredenberg 1992
23-43 TL	26						4%[bk,bs]	27%[bk,bs]		Rivers	158	10-12	*	PDC-CPS	240/15	1.6/10	Rect.	Fredenberg 1992
Large				~35%[ch]			<18%			Shocking tank			=	PDC-CPS	240/15	1.6/10	Rect.	Reynolds et al. 1992
adults?					X ? [g]				X ? [g]	Rivers etc,CRB			*	PDC-CPS	240/15	1.6/10	Rect.	Trammell pc

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality Short-term	Mortality Long-term	Brands	Spinal Injuries Spine/Vertebrae Extern.	Spinal Injuries Spine/Vertebrae Intern.	Spinal Injuries Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
***Oncorhynchus tshawytscha*, chinook salmon**																		
yoy, 7 TL	1843		0-77%♣							Lab shock tank	~50	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
yoy, 7 TL	499		2-59%♣							Lab shock tank	50 & 85	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-6 TL	1441	X♣	0-57%♣							Lab shock tank	~48	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
6-8 TL	889	X♣	1-78%♣							Lab shock tank	~48	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
8-10 TL	201	X♣	6-63%♣							Lab shock tank	~48	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
10-12 TL	269	X♣	5-58%♣							Lab shock tank	~48	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-10 TL	168		0-1%♣							Lab shock tank	43	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	323		0-7%♣							Lab shock tank	55	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	269		0-15%♣							Lab shock tank	83	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
6-10 TL	123		9-10%♣							Lab shock tank	133	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	215		0-13%♣							Lab shock tank	180	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	242		4-58%♣							Lab shock tank	283	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	52		8-75%♣							Lab shock tank	483	10-20	=	PDC	2	20	Rect.	Collins et al. 1954
4-10 TL	93		0%♣							Lab shock tank	53	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	115		0-18%♣							Lab shock tank	68	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-8 TL	83		0-3%♣							Lab shock tank	78	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	454		0-18%♣							Lab shock tank	103	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	283		4-28%♣							Lab shock tank	128	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	204		10-44%	♣						Lab shock tank	195	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-12 TL	174		15-59%	♣						Lab shock tank	303	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-10 TL	105		49-67%	♣						Lab shock tank	483	20-25	=	PDC	2	20	Rect.	Collins et al. 1954
4-6 TL	315		0-26%♣							Lab shock tank	~50 ?	14	=	PDC	2	20	Rect.	Collins et al. 1954
6-8 TL	449		0-53%♣							Lab shock tank	~50 ?	14	=	PDC	2	20	Rect.	Collins et al. 1954
8-10 TL	154		0-50%♣							Lab shock tank	~50 ?	14	=	PDC	2	20	Rect.	Collins et al. 1954
4-6 TL	132		0-55%♣							Lab shock tank	~50 ?	18	=	PDC	2	20	Rect.	Collins et al. 1954
6-8 TL	678		6-52%♣							Lab shock tank	~50 ?	18	=	PDC	2	20	Rect.	Collins et al. 1954
8-10 TL	294		10-80%	♣						Lab shock tank	~50 ?	18	=	PDC	2	20	Rect.	Collins et al. 1954
9 TL	446		4-58%♣							Lab shock tank	45-65	12-20	=	PDC	2	20	Rect.	Collins et al. 1954
9 TL	412		0-38%♣							Lab shock tank	45-65	12-20	=	PDC	8	20	Rect.	Collins et al. 1954
9 TL	260		0-53%♣							Lab shock tank	50	10-16	=	PDC	8	20	Rect.	Collins et al. 1954

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality: Short-term	Mortality: Long-term	Brands	Spinal Injuries: Spine/Vertebrae Extern.	Spinal Injuries: Spine/Vertebrae Intern.	Spinal Injuries: Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (μS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
9 TL	192		4-38%[a]							Lab shock tank	50	10-16	=	PDC	8	80	Rect.	Collins et al. 1954
4-6 TL	502		0-4%[a]							Lab shock tank	38-68	10-20	=	PDC	3-8	20	Rect.	Collins et al. 1954
6-8 TL	317		3-6%[a]							Lab shock tank	38-68	10-20	=	PDC	3-8	20	Rect.	Collins et al. 1954
8-10 TL	82		8-50%[a]							Lab shock tank	38-68	10-20	=	PDC	3-8	20	Rect.	Collins et al. 1954
10-12 TL	46		6-50%[a]							Lab shock tank	38-68	10-20	=	PDC	3-8	20	Rect.	Collins et al. 1954
4-6 TL	489		9-29%[a]							Lab shock tank	38-68	10-20	=	PDC	10-15	20	Rect.	Collins et al. 1954
6-8 TL	548		0-28%[a]							Lab shock tank	38-68	10-20	=	PDC	10-15	20	Rect.	Collins et al. 1954
8-10 TL	89		48-71%	[a]						Lab shock tank	38-68	10-20	=	PDC	10-15	20	Rect.	Collins et al. 1954
10-12 TL	27		73-75%	[a]						Lab shock tank	38-68	10-20	=	PDC	10-15	20	Rect.	Collins et al. 1954
***Prosopium cylindraceum*, round whitefish**																		
juv.-ad.			0		X					Streams	25-200	5-15	•	PDC?				Valdez pc
***Salmo trutta*, brown trout**																		
5-30			~0 [ca]							Stream (box)			•					Chmielewski et al. '73
~19 TL	40		20% [cm]							Hatch. raceway	306 @25C		•	AC				Pratt 1955
~19 TL	49		4% [cm]							Hatch. raceway	306 @25C		•	DC				Pratt 1955
[ch]	20		0-6% [ch]							Stream, dip net			•	DC,500V				Lamarque '67a&b, '90
[ch]	20		0-17%[ch]							Stream, dip net			•	DC,400V	[ci]			Lamarque '67a&b, '90
30-51 TL	50						8% [by]	6% [by]		Rivers	300	6-12	•	DC				Fredenberg 1992
31-45 TL	50						32%[ca]	28%[ca]		Rivers	300	6-12	•	Hybrid [bz]	60	<8 ?	½ Sine	Fredenberg 1992
17-51 TL	28 [cc]		≤4% [cc]				86%			Rivers	299		•	Various[cd]				Meyer & Miller 1990[ce]
yoy-ad					X [v]					Rivers, CRB	<25?-1000	0-19	•	PDC				Buntjer pc
			~0.01%		X					Rivers, CRB	300-2000	5-25	•	PDC				Valdez pc
			0		X	0				Rivers, CRB	500-800	15-25	•	PDC				Valdez pc
[ch]	20		0-86%[ch]							Stream, dip net			•	PDC		[cj]	Expo.	Lamarque '67a&b, '90
[ch]	20		0-93%[ch]							Stream, dip net			•	PDC		[ck]	Expo.	Lamarque '67a&b, '90
[ch]	20		0-50%[ch]							Stream, dip net			•	PDC [cl]	5	66	Rect.	Lamarque '67a&b, '90
17-38 TL	31 [ch]						26% [ch]			Rivers	340-350	7-8	•	PDC	40	5	Rect.?	WY Game Fish '91 [cj]
17-41 TL	34 [ci]						15% [ci]			Rivers	340-350	7-8	•	PDC	40	5	Rect.?	WY Game Fish '91 [cj]
	•				50%	0 ?	50% ?			Rivers etc,CRB	<50->5000	>0->30	•	PDC	60			Krueger pc
adults? [ca]			≤0.5%							Streams	<100-200	<10-15	•	PDC? [ce]	60? [ce]	<8? [ce]	½Sine?	Nehring 1991

Table 3. (Continued)

SPECIES: Lengths (cm) or Develop. Intervals	SPECIES: No. Obs.	ADVERSE EFFECTS: Delayed Equil. Recov.	Mortality: Short-term	Mortality: Long-term	Brands	Spinal Injuries: Spine/Vertebrae Extern.	Spinal Injuries: Spine/Vertebrae Intern.	Spinal Injuries: Intern. Hemor.	Other Injuries	ENVIRONMENT: Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	ELECTRIC FIELD: Current Type	Frequency (Hz)	Pulse Duration (ms)	Wave-form	SOURCE (pc = pers. commun.) (um = unpubl. ms.)
adults? [m]			<1-5%			<1-5%				Streams	<100-200	<10-15	*	PDC? [cp]	60? [cp]	<8? [cp]	½Sine?	Nehring 1991
30-56 TL	50						36% [cb]	56% [cb]		Rivers	300	6-12	*	PDC	60	8	½ Sine	Fredenberg 1992
28-54 TL	17		35%? [cf]				82%			Rivers	600-616		*	PDC	60	7	Rect.?	Meyer & Miller 1990
"	20		27-89%	"						Stream, dip net			*	PDC [m]	90	~11	½ Sine	Lamarque '67a&b, '90
13-59 TL	8		"				25%			Rivers	600-616		*	PDC-CPS	240/15	1.6/10	Rect.	Meyer & Miller 1990
16-39 TL	59 "						14%			Rivers	340-350	7-8	*	PDC-CPS	240/15	1.6/10	Rect.	WY Game Fish '91 [cj]
***Salvelinus confluentus*, bull trout**																		
juv.-ad.			0		X ♠					Streams	25-200	5-15	*	PDC?				Valdez pc
***Salvelinus fontinalis*, brook trout**																		
~9-24 TL	"							22% [cr]		Streams	very low		*	AC				Hollender 1992
~25 TL	47		11% [cw]							Hatch. raceway	306 @25C		*	AC				Pratt 1955
12-24	375		0.5% ♠		2% ♠		♠			Hatch. raceway	10	6	*	AC,350V	300			Hudy 1985
12-24	375		0.2% ♠		2% ♠		♠			Hatch. raceway	10	6	*	AC,700V	300			Hudy 1985
12-24	375		0.2% ♠		1% ♠		♠			Hatch. raceway	10	6	*	AC,760V	250-300			Hudy 1985
~25 TL	50		0% [cr]							Hatch. raceway	306 @25C		*	DC				Pratt 1955
~9-24 TL	"							26% [cr]		Streams	very low		*	PDC				Hollender 1992
juv.-ad.			0		X					Streams	25-200	5-15	*	PDC?				Valdez pc
yoy-ad					X [*]					Rivers, CRB	<25?-1000	0-19	*	PDC				Buntjer pc
***Salvelinus malma*, Dolly Varden**																		
juv.-ad.		high		low [*]	high					Streams		5-15	*	AC	60			Valdez pc
***Salvelinus namaycush*, lake trout**																		
adults [bf]			0		0	0				Lakes		1-5	*	PDC				Valdez pc
***Thymallus arcticus*, Arctic grayling**																		
37-45 TL	25						0%	0%		Streams	33	6	*	DC				Fredenberg 1992
39-43 TL	25						0%	4%		Streams	33	6	*	Hybrid [bc]	60	<8 ?	½ Sine	Fredenberg 1992
juv.-ad.			0		X					Streams	25-200	5-15	*	PDC?				Valdez pc
12-37 FL	88		3% [m]		16% [p]	5%	63% [ck]	27% [ck]		Rivers	60-88	9-15	*	PDC	40-120	3.3-10		Holmes et al. 1990
23-39 FL	616/60[t]		1%(+?)[cl]		27% [m]		62% [m]	25% [m]		Rivers	39-40	9-11	*	PDC	80	5		Holmes et al. 1990
20-41 FL				~0% [m]						Rivers, lakes	>39	8-11	*	PDC	80	5		Holmes et al. 1990
20-32 FL	103/60[t]		4% [p]		0%		0-3% [m]	5% [m]		Rivers	80-88	10-11	*	PDC	80	5		Holmes et al. 1990

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality: Short-term	Mortality: Long-term	Brands	Spinal Injuries: Spine/Vertebrae: Extern.	Spinal Injuries: Spine/Vertebrae: Intern.	Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
Gadidae																		
***Lota lota*, burbot**																		
juv.-ad.			0		0					Streams	25-200	5-15	*	PDC?				Valdez pc
Gasterosteidae																		
***Gasterosteus aculeatus*, threespine stickleback**																		
juv.-ad.		high		low *	high					Streams		5-15	*	AC	60			Valdez pc
Centrarchidae																		
***Lepomis cyanellus*, green sunfish**																		
7-13 TL	51		10% ♣							Ponds	>66, <520	0-4	*	AC	180♣		♣	Schneider 1992
***Lepomis gibbosus*, pumpkinseed**																		
6-20 TL	174		0-1% ♣							Lakes	>66, <520	13-28	*	AC	180♣		♣	Schneider 1992
67-20 TL	100		2-12%[cc]							Lakes	>66, <520	16-28	*	AC	180♣		♣	Schneider 1992
7-12 TL	352		9% ♣							Ponds	>66, <520	0-4	*	AC	180♣		♣	Schneider 1992
***Lepomis macrochirus*, bluegill**																		
8-10	525	♣	1-19%[dd]				3-7%[dd]			Hatch. ponds	167		*	AC,115V	60			Spencer 1966 &1967
8-10	1200		0-75%[cc]							Hatch. ponds	167		*	AC,230V	180 ♣		♣	Spencer 1966
8-10	25		4%♣							Hatch. ponds	100		*	AC,230V	180 ♣		♣	Spencer 1966
8-10	25		18%♣							Hatch. ponds	200		*	AC,230V	180 ♣		♣	Spencer 1966
8-10	25		24%♣							Hatch. ponds	250		*	AC,230V	180 ♣		♣	Spencer 1966
8-10	25		40%♣							Hatch. ponds	333		*	AC,230V	180 ♣		♣	Spencer 1966
8-10	25		54%♣							Hatch. ponds	500		*	AC,230V	180 ♣		♣	Spencer 1966
8-10	25		56%♣							Hatch. ponds	1000		*	AC,230V	180 ♣		♣	Spencer 1966
8-10	525	♣	1-58%[dd]				9-16%[dd]			Hatch. ponds	167		*	AC,230V	180 ♣		♣	Spencer 1966 &1967
5-18 TL	44		0-0% ♣							Lakes	>66, <520	13-18	*	AC	180♣		♣	Schneider 1992
5-20 TL	102		2-2% ♣							Lakes	>66, <520	22-26	*	AC	180♣		♣	Schneider 1992
7-12 TL	166		1% ♣							Ponds	>66, <520	0-4	*	AC	180♣		♣	Schneider 1992
8-10	525	♣	1-29%[dd]				0-3%[dd]			Hatch. ponds	167		*	DC,115V				Spencer 1966 &1967
9-17		=	0-95%[==]							Lab. tank	154	10	=	PDC	2,9,17			Whaley et al. 1978
***Micropterus* spp., black basses**																		
	*				0	0	0 ?			Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS								ENVIRONMENT				ELECTRIC FIELD				SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality: Short-term	Mortality: Long-term	Spinal Injuries: Brands	Spinal Injuries: Spine/Vertebrae Extern.	Spinal Injuries: Spine/Vertebrae Intern.	Spinal Injuries: Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Waveform	(pc = pers. commun.) (um = unpubl. ms.)
***Micropterus salmoides*, largemouth bass**																		
13-25	100/70		~0%[a]				0%[ad]			Hatch. ponds	167		*	AC,230V	180 [a]		[a]	Spencer 1966 &1967
	30		~0% [a]							Lakes	>66, <520		*	AC	180[a]		[a]	Schneider 1992
Percidae																		
***Etheostoma flabellare*, fantail darter**																		
2.5-7.5		[m]	0-95%[m]							Lab. tank	154	10	=	PDC	2,9,17			Whaley et al. 1978
***Perca flavescens*, yellow perch**																		
5-10 TL	40		0-0% [ad]						X [ad]	Lakes	>66, <520	10-15	*	AC	180[a]		[a]	Schneider 1992
8-13 TL	66		0-0% [a]						X [a]	Lakes	>66, <520	6-8	*	AC	180[a]		[a]	Schneider 1992
10-27 TL	52		0-9% [ad]							Lakes	>66, <520	7-13	*	AC	180[a]		[a]	Schneider 1992
9-19 TL	16		94% [ad]							Lakes	>66, <520	19-27	*	AC	180[a]		[a]	Schneider 1992
***Stizostedion vitreum*, walleye**																		
	13		~0% [a]							Lakes	>66, <520		*	AC	180[a]		[a]	Schneider 1992
33-44 TL	5						40%			Lakes			*	PDC?				Newman 1991
19-48 TL	12						25%			Rivers	17,800 ? [c]	26	*	PDC	30			Newman 1991
					0	0	0 ?			Rivers etc,CRB	<50->5000	>0->30	*	PDC	60			Krueger pc
33 ? TL	1						0	0		Rivers	600	11	*	PDC	60	8 ?	Rect.	Fredenberg 1992
18-43 TL	13						31%			Lakes	15,300 ? [c]	22	*	PDC	120			Newman 1991
***Stizostedion canadense*, sauger**																		
≥47 TL	20						0%	0%		Rivers	~500	7	*	PDC	60	8 ?	Rect.	Fredenberg 1992
32-53 TL	6						0%	0%		Rivers	600	11	*	PDC-CPS	240/15	1.6/10	Rect.	Fredenberg 1992
Cottidae (unspecified species)																		
		often [m]	often [m]							Riffles	<100		*	PDC				Gowan pc
***Cottus bairdi*, mottled sculpin**																		
3-9 SL	90		0-3% [a]							Streams	10-15	5-8	*	DC				Barrett & Grossman'88
4-9 SL	~57		0-12% [a]							Streams	10-15	14-16	*	DC				Barrett & Grossman'88
4-8 SL	50		35-60%	[a]						Exp. channel		12-14	*	DC				Barrett & Grossman'88

Table 3. (Continued)

SPECIES		ADVERSE EFFECTS							ENVIRONMENT			ELECTRIC FIELD					SOURCE
Lengths (cm) or Develop. Intervals	No. Obs.	Delayed Equil., Recov.	Mortality: Short-term	Mortality: Long-term	Spinal Injuries: Brands	Spinal Injuries: Spine/Vertebrae Extern.	Spinal Injuries: Spine/Vertebrae Intern.	Spinal Injuries: Intern. Hemor.	Other Injuries	Where fish were subjected to electric field	Conductivity (µS/cm)	Temp. (°C)	Fd Tp	Current Type	Frequency (Hz)	Pulse Duration (ms)	Wave-form	(pc = pers. commun.) (um = unpubl. ms.)
General (unspecified families or species)																		
		X[n]			X					Rivers, reserv.			*	all				Beyers pc
juv-ad[b,d]							0[b,c]			Rivers etc,CRB	250-3500		*	PDC,DC				Burdick pc
			>0.1%[m]							Rivers, streams	<100		*	PDC				Gowan pc
[b,e]			0?			0				Rivers, CRB			*	PDC				Kinsolving pc
[b,e]			~0.01%		0					Rivers, CRB	300-2000	5-25	*	PDC				Valdez pc
4-96		X	[b,e]		X					Rivers etc,CRB			*	PDC				Trammell pc
4-96		X	[b,e]		X					Rivers etc,CRB			*	PDC-CPS	240/15	1.6/10	Rect.	Trammell pc

Footnotes:

[a] Abbreviations in and comments on table headings:
Develop. = developmental; No. Obs. = number of fish observed (i.e., examined, X rayed, or necropsied); Delayed Equil., Recov. = delayed equilibrium or recovery; Short-term mortality is immediate to several days; Brands are sometimes referred to as burns or bruises and usually indicate spinal damage; Extern. = external signs of spinal damage other than brands (e.g., bent back); Intern. = internal observations of damage to the spine or vertebrae based on X-ray analysis or necropsy (regardless of severity rating); Intern. Hemor. = internal hemorrhages observed along or in tissues around the spine during necropsy (regardless of severity rating); µS/cm = microsiemens per centimeter; Temp. = temperature; °C = degrees Celsius; Fd Tp = field type (heterogeneous or homogeneous); Hz = hertz; ms = milliseconds; pc = personal communication; um = unpublished manuscript.

[b] Abbreviations in body of table: TL = total length; FL = fork length; juv. = juveniles; ad. = adults; yoy = young-of-the-year juveniles; X = one or more observations but quantity not specified; "~" = approximately; "<" = less than; ">" = greater than; Lab. = laboratory; CRB = Colorado River Basin; reserv. = reservoirs; "*" = heterogeneous field (voltage gradient diminishes with distance from electrodes); "=" = Homogeneous field (voltage gradient constant); AC = alternating current; DC = (continuous) direct current; PDC = pulsed direct current; CPS = trademark for a specific pulse train by Coffelt Manufacturing, Inc. (complex pulse system–trains of three 1.6-ms, 240-Hz pulses at 15 Hz); Rect. = rectangular; Expo. = exponential; ¼ Sine = quarter sine; ½ Sine = half sine (rectified AC).

[c] Mortalities due to notochords that were "completely blown apart."

[d] Specimen were subjected to 2 to 4 5-s electric field exposures within a 6-week period, at least 7-d apart; they were acclimated to test conductivities 2.5-7 d prior to the test and observed for 3 d after exposure.

[e] Fish were captured and filleted for contaminants analyses

[f] Only injury was considered a freak accident–specimen was trapped between a plate cathode and the boat.

[g] Hemorrhaging (brands ?) seemed proportionately greater in Grand Canyon electrofishing using CPS system than in Upper Colorado River Basin using a more typical PDC.

[h] Only 1 injury was observed, a brand on a specimen suspected to have touched the cable anode; it and fish knocked out completely and floating on surface recovered slowly but all seemed fine on release. Specimens that were subsequently recaptured or followed after radiotagging appeared normal.

[i] Twenty fish were captured by electrofishing, radiotagged, and followed for 4 months (except one that subsequently died of unknown causes).

[j] Large Colorado squawfish which contacted the anode bled at the gills and "everything"; a 112 mm specimen that was captured belly-up with gills still going and no obvious bleeding died (viscera were removed for study and the remainder of the fish was preserved).

[k] Large female with bruise (might be same fish reported by McAda pc[h]); single and multiple recaptures appeared normal.

[l] Brands usually observed in caudal region.

[m] Twenty fish were captured by electrofishing, radiotagged, and followed for 4 months (except two that were lost).

[n] No visible external injuries or high mortality observed, but fish were typically "knocked out cold" and floated slowly to the water surface.

[o] Most were completely tetanized, "stiff as boards," and floated to the surface behind the boat.

[p] Injuries from electrofishing in previous years–back half of fish stopped growing and the fish started to look like footballs.

[q] Several unspecified injuries among salmonids; necropsied fish same as those reported by Krueger pc.

[r] No immediate mortality; short-term mortality among seined controls was higher (12%), but most mortality among

Table 3. (Continued)

electrofished specimens occurred on day 1 of the 7-d holding period whereas most seining mortalities (controls) occurred on day 7.

[s] Spinal injury was higher (9%) and sometimes more severe among seined controls. Hemorrhage was nearly the same for seined controls (5%). None of the injuries observed among electrofished specimens were considered new electrofishing injuries since hemorrhages were not observed in association with specific vertebral damage and since injuries appeared as great or greater among seined controls. However, hemorrhages may have cleared up during the 7-d holding period.

[t] Of the short-term mortalities, 10% were immediate; mortalities among seined controls, immediate and after 7 d, were as great or greater (8% and 42%); mortalities for controls occurred throughout the 7-d holding period, whereas most mortalities for electrofished specimens occurred during the first day.

[u] Spinal injuries, internal hemorrhages, and external hemorrhages were as great or greater among seined controls (2%, 19%, and 42%). No spinal injuries were considered new electrofishing injuries.

[v] Brands were hemorrhages immediately below and posterior to the dorsal fin and were observed on young-of-the-year as well as older fish.

[w] Yellowstone cutthroat trout.

[x] High percentage of fish recaptured 1 and 2 years later.

[y] *Oncorhynchus mykiss* taken within 0.5 m of the electrode seemed likely to be injured.

[z] Numbers of fish observed for: short-term mortality and bruises/spinal damage and hemorrhages.

[aa] Of mortalities during the 4-d holding period, 4% were immediate.

[ab] Vertebral damage and hemorrhage data was based on the 10 mortalities and 22 of the survivors > 40 cm FL; of fish over 40 cm in length, 41% of the survivors suffered major spinal injury and 53% suffered either major spinal injury or death.

[ac] Spinal injury was posterior to dorsal fin; based on external examination only.

[ad] Fish were frozen, X-rayed, and necropsied; those found to have spinal injuries also had associated internal hemorrhages and splintered bones from compression fractures. Twelve hatchery specimens were used as non-electrofished controls.

[ae] Fish were held perpendicular to the lines of current in a plastic cage.

[af] Fish were held parallel to the lines of current in a plastic cage.

[ag] Negligible, only one mortality in a whole series of tests. Indices of fatigue, 20-240 s (mostly under 60 or 120 s), varied with electrofishing equipment, increased with field intensity and fish length, and decreased with successive exposures.

[ah] Brands noted on larger specimens.

[ai] No immediate mortality, but all deaths occurred within the first 4 hr.

[aj] Brands disappeared by the end of the 7-d holding period; all branded specimens had associated spinal injuries.

[ak] Based on presence of both vertebral damage and hemorrhage in the same location, 17% (21% including mortalities) of the fish determined to have new electrofishing injuries; however, after a 7-d holding period, most hemorrhages may have already dissipated. Fish collected by hook & line (N=11) experienced no mortality, 18% vertebral damage, and no hemorrhages.

[al] All short-term mortality was immediate; fish were not held beyond normal processing.

[am] Seven fish with spinal injuries had associated brands.

[an] Hemorrhages were observed at the same location as vertebral damage in 18% of the fish. Beach seine and hook and line collections yielded 2% immediate mortality, 5% with vertebral damage; and 13% with internal hemorrhages.

[ao] Long-term mortality was not significantly different from that for other gear based on year-after recapture rates in a river and a lake. Growth rates for fish 30 cm and greater were not significantly different for fish after one year in the lake; data was insufficient to determine significance of growth differences for smaller fish and for those from a river.

[ap] Short-term, 7-d mortality was lower than for fish collected by other gear (6%); none was immediate.

[aq] Some spinal injuries and hemorrhages were greater (12% and 10% respectively) among fish collected by beach seine or hook and line. Regardless of gear, vertebral damage and hemorrhages were not observed in the same locations; however, hemorrhages may have begun to clear up prior to specimen analysis.

[ar] No mortalities were reported after 1 month for either electrofished (N=140) or control (N=70) specimens (death of all fish in one of five holding ponds was considered an accident). N=174 fish examined for spinal injury.

[as] Short-term mortality was immediate (no fish were held); mortality for controls was greater (2% for hook and line, 1% for gill nets, and 23% for trap nets) than for electrofished specimens.

[at] Long-term recapture rates were 9% for controls and 5% for electrofishing. Long-term growth was not significantly different.

[au] Incidence of vertebral damage and hemorrhages was 1% and 3%, respectively, for fish taken by hook and line, fyke trap, and gill nets. Based on presence of both vertebral damage and hemorrhages at the same location, 13% of electrofished specimens were considered to have new electrofishing injuries.

[av] All fish with hemorrhages also had obvious and severe vertebral damage.

[aw] Mortality increased progressively with duration of exposure and pulse rate; mortality ranged from low or negligible at or below 15 s and even ~65 s at very low frequency (1.6 Hz) to 95% at 180 s and 16 Hz). Recovery time also increased with length of exposure. Fish were held parallel to the lines of current.

[ax] Electrofished sculpins commonly flared their gills and often died.

[ay] Some fish required 5-10 minutes for recovery of equilibrium.

[az] More than 5000 fish held overnight in baskets to assess mortality; most were salmonids under 18 inches.

[ba] Never observed death due to obvious injuries.

[bb] Fish in general, except as noted above for *Cyprinus carpio* and *Oncorhynchus mykiss* by Kinsolving pc.

[bc] Fish other than species listed above by Valdez pc.

[bd] Fish other than Upper Colorado River Basin salmonids and endangered species listed above by Burdick pc.

[be] Necropsied fish same as those reported by Krueger pc.

[bf] Brood stock: a 20-pound female and 2 to 5-pound males. Eggs fertilized well and survival was high.

[bg] Duty cycle.

[bh] Delayed mortality during 35-d holding period might have been short-term rather than long-term but no immediate mortality and delayed mortality was less than for controls (5%) or fish subjected to fly fishing (5% initial and 3% delayed). The authors specifically noted that brands resulted from internal hemorrhages and possible

Table 3. (Continued)

breakage of the vertebral column. Stamina based on a swimming performance index the day after treatment was significantly lower for electrofished than control or fly-fished specimens.

[bi] No immediate mortality. Mortality for yearling juveniles over 1.4 yr was similar to controls (7% versus 8% for controls). Survival and growth to spawning, fecundity, and survival of offspring (eggs and larvae) were similar for both exposed and control fish. Voltage gradient was 0.75 V/cm, exposure was 30 s, and 4-84% of the fish were narcotized by the current. Waveform pulses were described as having an exponential leading edge and a rectangular trailing edge (rectangular waveform with a leading edge spike?).

[bj] No immediate mortality. Data for the first 4 months were not properly recorded and are unknown (< 10%); the number of exposed fish were reduced to 856 at that point and from the 4th month to 2.5 yr after exposure, mortality was less than for controls (10% versus 16% for controls with numbers of exposed fish again reduced to 236 for the last half year of observations). Survival and growth to spawning, fecundity, and survival of offspring (eggs and larvae) were similar for both exposed and control fish. Voltage gradient was 1.0 V/cm, exposure was 30 s, but none of the yoy were narcotized. Waveform pulses were described as having an exponential leading edge and a rectangular trailing edge (rectangular waveform with a leading edge spike?).

[bk] Similar X-rays of 104 gill-net-caught, fish-trap-caught, and hatchery *Oncorhynchus mykiss* revealed no vertebral damage; similar necropsy of 16 gill-net-caught and 50 fish-trap-caught *Oncorhynchus mykiss* revealed 13% and 4% with spinal-region hemorrhages, respectively, but all were minor (class 1 by Reynold's um 1992 classification).

[bl] 30% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bm] 18% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bn] According to Fredenberg's (1992) note on page 8 of his text, current was suspected to be PDC rather than DC as originally recorded and reported in Fredenberg's appendix B data.

[bo] 98% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both; sample was a mixture of 35 *Oncorhynchus mykiss* and 7 *Oncorhynchus clarki*.

[bp] 78% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bq] Sample was a mixture of 9 *Oncorhynchus mykiss* and 3 *Oncorhynchus clarki*.

[br] 55% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bs] 31% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bt] 73% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bu] 90% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both; sample was a mixture of 31 *Oncorhynchus mykiss* and 8 *Oncorhynchus clarki*.

[bv] 65% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bw] 64% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both; hybrid current with PDC above half-voltage DC (referred to as a half-pulse waveform by Fredenberg 1992).

[bx] All branded fish (N=39) were X-rayed, necropsied, and found to have spinal injuries, 64% of which were classified as moderate to severe; among unbranded fish (N=113), 50% suffered vertebral damage or (and) spinal-region hemorrhages, 30% of which were classified as moderate to severe; fish were collected from the same river using DC and PDC (60-Hz rectangular and CPS).

[by] 10% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[bz] Hybrid current with PDC above half-voltage DC (referred to as a half-pulse waveform by Fredenberg 1992).

[ca] 44% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[cb] 62% injured overall, i.e., specimens with only vertebral damage revealed by X-rays, only spinal-region hemorrhages revealed by necropsy, and both.

[cc] Initially, 150 fish were retained for post-electrofishing observation, but only 88 fish were recovered 7 d later due to holes in the in-river pen net.; of these 4 *Oncorhynchus mykiss* and 1 *Salmo trutta* died. None of the deaths were immediate. 50 *Oncorhynchus mykiss* and 28 *Salmo trutta* were examined by X ray and necropsy.

[cd] Most of the fish were presumably taken with DC; characteristics of the PDC current used were uncertain due to a control box that was found to be "seriously out of calibration."

[ce] Also reported by Wyoming Game and Fish Department 1990.

[cf] deaths for fish taken by 60-Hz PDC occurred in the hatchery truck during transit and were probably due to stresses in addition to electrofishing (any occurrences of immediate mortality were not reported).

[cg] No immediate mortality.

[ch] Fish from stream segment electrofished with 4 passes.

[ci] Fish from stream segment electrofished with only 1 pass.

[cj] Also reported by Meyer and Miller 1991 (abstract) and um 1991.

[ck] Combined mortality for fish subjected to DC, PDC, and CPS during a 203 d holding period in a hatchery; most deaths occurred in the first 30 d (factors other than or in addition to electric currents may have responsible).

[cl] Number captured and examined for brands after first exposure (two passes through 5-m wide raceways) / number captured by a second electrofishing effort (again two passes) 7 d later and necropsied for spinal hemorrhages or anomalies later; controls showed no signs of spinal hemorrhages or anomalies. Mortalities were for 7 d period after first exposure, N =~30 fish per trial.

[cm] Also reported by McMichael et al. 1991 (abstract).

[cn] Account covers and is recorded here under both *Oncorhynchus mykiss* and *Salmo trutta*.

[co] Walk electrofishing using Coffelt VVP-2C, assumed to output 60-Hz, ½-sine PDC.

Table 3. (Continued)

- Boat electrofishing using Coffelt VVP-2C, assumed to output 60-Hz, ½-sine PDC.
- N=579 for both AC and PDC electrofishing combined.
- Among 89 fish captured by angling, less than 7% had internal hemorrhages or damage to the spine; incidence of injury (hemorrhages or spinal damage as documented by X ray and necropsy) varied with size from 14% for fish <13 cm to 42% for those >18 cm TL.
- Reported conductivity or units seem unlikely–17.8 mS/cm for the river and 15.3 mS/cm for the lake.
- fish were held for 10 d and mortality was delayed; comparable mortality for fish captured by seining (N=16) and angling to exhaustion (N=16) was 6% and 87% respectively.
- Based on X rays, 4% of the fish were found to have vertebral anomalies before exposure to the electric current with no change afterward.
- Other injuries noted included hemorrhaging from the gills or vent, hemorrhaging in the skin around the vent, dilated and clotted blood vessels in the region of the brain, intestine protruding from the vent, and persistent paralysis suggesting injury to the nervous system.
- Most of these mortalities were immediate (mostly fish that escaped the scap net and suffered extensive exposure to the current); no mortalities occurred among controls. Fish were exposed to the current at the beginning, middle, and end of a 6-wk holding period by holding them in the field with a scap net for 15 s about 30 cm from an electrode (positive electrode in DC).
- All mortalities were delayed; no mortalities occurred among a similar number of controls. Fish were exposed to the current at the beginning, middle, and end of a 6-wk holding period by holding them in the field with a scap net for 15 s about 30 cm from an electrode (positive electrode in DC).
- Immediate mortality; immediate mortality among controls (N=403) was 2%. Comparing treatments, rectangular rather than half-sine waveforms, higher frequencies (30 vs. 15 Hz) and higher water conductivities (67 & 100 vs. 200 & 1000 µS/cm) resulted in higher mortality. Fish were forced through an electrical array of 5 rows of electrodes with a cyclic pattern of positive-negative electrode configurations that changed with every pulse. Fish were held for 30 d; except for frequency, patterns of differences among treatments for delayed mortality (generally between 7% and 18%) were similar to those for immediate mortality but not significantly different from controls.
- Mortality was highly correlated with exposure times from 1% at 1 s (0% at 4 s) to 75% at 300 s; for exposures ≥60 s, most mortalities were immediate, occurring during the first 5 min. of the 24 h holding period; for lesser exposures, most mortalities were delayed but occurred within the first 2 h.
- 3-phase, 230V AC; 3 sine waveforms phase shifted by a third.
- Exposure time was 60 s; most mortality occurred in the first 2 h and generally a third to a half was immediate.
- Recovery time for survivors increased with exposure time (and was greater for 230-V, 180-Hz, 3-phaese AC than 115-V, 60-Hz, single-phase AC).
- Exposure times varied from 1 to 120 s; mortality increased with exposure time but did not correlate well with incidence of injury; incidence of injury was independent of exposure time; most mortality occurred during the first 2 h of the 24 h holding period.
- Fish held parallel to a field of 6 V/cm for 60 s.
- Fish held perpendicular to a field of 6 V/cm for 60 s.
- N=100 for mortality; N=70 for spinal injuries. Exposure was varied from 1-300 s and fish were held for 24 h. Only one mortality was recorded (60 s, delayed) and this was believed to be due to handling rather than the electric current.
- Three or four passes; 15 d holding period; immediate mortality less than 1%; no mortality among controls. Data combined for burns and other external signs of spinal injury (erratic swimming) based on both *Oncorhynchus mykiss* and *Salvelinus fontinalis*; no external signs of injury observed among controls.
- 2.5% of all 2250 *Oncorhynchus mykiss* and *Salvelinus fontinalis* examined are estimated to experienced spinal injury (6 of 28 dead, 27 of 36 abnormal, and 23 of 2186 normal fish, latter extrapolated from observation of one injury among 96 normal fish examined); no injured vertebrae among controls.
- Mortality not significantly different from similar numbers of kick-seine "controls" (0-12% for fish collected in late winter at 5-8°C; 0-14% for fish collected in early summer at 14-16°C); single exposure at 600V; 30 d holding period.
- Mortality not significantly different from similar numbers of repeatedly handled kick-seine "controls" (45-50%); probably most affected by repeated handling; multiple exposures, once per week for a month at 600V; monitored between treatments.
- Little or no mortality during 30 d observation period.
- Mortality increased with exposure time (0.5-20 min) and voltage gradient (1, 2, and 4 V/cm).
- Mortality increased with exposure time (2-10 min) and less consistently with water conductivity (and thereby current density); voltage gradient was constant at 2 V/cm.
- Immediate mortality (1 h observation period), 30 s exposure; mortality increased with voltage gradient from the low value at 3-4 V/cm to the high value at 15 V/cm; no size effect; mortality among 2800 controls was 0.5%.
- Immediate mortality (1 h observation period), 30 s exposure at a constant 4 V/cm.; mortality increased with water conductivity (and therefore current density); at higher conductivities, mortality tends to be greater at higher temperatures. No consistent size effect; mortality among 2800 controls was 0.5%.
- Voltage gradient constant at 4 V/cm; mortality increased with exposure time and temperature (values at 14°C tend to be less than at 18°C); also tends to increase with size.
- Voltage gradient held constant at 2V/cm; mortality increased with exposure time (3-10 min for trials at 2 Hz and 0.5-3 min for 8 Hz) but occurred at shorter exposures times for 8 Hz than for 2 Hz (cumulative current on time 4 times greater at 8 Hz).
- Voltage gradient held constant at 2V/cm; mortality increased with exposure time (0.5-3.0 min) but tended to be higher for the shorter pulse duration (20 ms versus 80 ms).
- Voltage gradient held constant at 4V/cm, 30 s exposures; mortality tended to increase with pulse rate and specimen size, but results could be confounded by variable conductivities.
- N = number exposed/ number necropsied. 80 fish exposed for 5 s, 80 for 10 s, and 80 for 20 s, then held 13 d for observation; mortality similar among 80 controls suggesting no effect by electrofishing. Necropsy of 3 electrofished and 1 control fish that had died during the holding period revealed no signs of spinal injury.
- 25 fish exposed for 5 s, 25 for 10 s, and 25 for 15 s; mortality among controls was also 0%.

Table 3. (Continued)

[dw] Fish were subjected to 1 min at 0.5 V/cm to initiate narcosis then held in narcosis at 0.25 V/cm for 1, 2, 4, or 6 h, (N=15 plus 15 controls each), then held for 25 d; all mortalities (2) occurred in fish narcotized for 6 h; fish narcotized for 1 or 2 h recovered instantaneously whereas those narcotized for 4 or 6 h had difficulty resuming swimming activity for up to 12 h. Photonegative behavior and growth during the holding period did not differ from that of controls.

[dx] Held for 1 d in cages in the lake.

[dy] Held for 10 d in pond; some mortalities were probably due to the stress of handling and incomplete recovery of all fish upon draw-down of the pond rather than electrofishing itself.

[dz] Held for 1-4 d in cages in the lake.

[ea] Held for 22 d in cages in the lake.

[eb] Held for 31 d in cages in the lake.

[ec] Based on comparable recapture rates 1 to 2 yr after initial capture by electrofishing, trap net, and angling (largemouth bass only); growth also appeared to be unaffected by capture method (although angled *Micropterus salmoides* were notably younger and larger upon capture and had grown most between initial capture and recapture.

[ed] Held for 3 d in cages in the lake; half of the fish (20) held were selected from among fish with obvious aggregations of blood in the sinus venosus near the base of the gills, the other half were selected from those without such an aggregation of blood; The aggregations of blood dissipated within 1 d and the fish seemed otherwise normal.

[ee] Held for 10 d in cages in the lake; half of the fish held (33) were selected from among fish with obvious aggregations of blood in the sinus venosus near the base of the gills, the other half were selected from those without such an aggregation of blood; The aggregations of blood dissipated within 1 d and the fish seemed otherwise normal.

[ef] Held for 30-38 d in cages in the lake.

[eg] Held for 40 d in cages in the lake; mortality likely due to stress of handling, confinement, low food, and high temperatures rather than electrofishing.

[eh] Species assumed to be *Salmo trutta*. 10 fish held in net 50 cm from positive electrode (lower mortality value) and 10 held 20 cm from positive electrode (higher mortality value); fish exposed for 20 seconds initially facing positive electrode; all mortality assumed to be immediate.

[ei] Rippled DC, generated by smoothing half-wave, rectified AC.

[ej] 50% duty cycle but frequency not reported.

[ek] 33% duty cycle but frequency not reported.

[el] 400 V.

[em] 400 V; full-wave rectified AC.

[en] 62-145 V (up to 180 V ?) for 5-30 s; recovery delayed in some fish to beyond a minute at higher energy densities (125 and 188 millijoules/cm^3); longer fish, especially those about 80 mm TL or longer required longer recovery times; fish requiring more than 2 minutes recovery time frequently died.

Bleeding from the gills was perhaps first reported as an electrofishing injury by Hauck (1949) in his description of injuries to rainbow trout. However, it seems to be particularly prevalent among mountain whitefish (*Prosopium williamsoni*) electrofished in Montana regardless of the type of current or equipment used (Fredenberg pers. commun.). According to Fredenberg (pers. commun.), "it is not unusual, on some streams, to see literally dozens of mountain whitefish come to the electrode under taxis with blood streaming in the water." Neither the specific cause of this injury, nor its relationship to other types of electrofishing injuries or subsequent survival have been investigated.

Respiratory failure is probably the leading cause of mortality in electrically stunned fish. Because respiration essentially ceases in fully tetanized fish (and may be reduced during narcosis), fish that are stunned and not removed soon enough from the electric field will likely die of asphyxiation. Synaptic fatigue occurs when fish are overexposed to a tetanizing current and results in a continuation of tetany for an extended period after removal from the field (Lamarque 1990; condition referred to as post-tetanic potentiation). Schreck et al. (1976) observed that after the current was switched off, tetanized rainbow trout either did not resume breathing for 60 s or they "coughed" violently for the first 30 s. Once breathing did resume, hypoxic conditions were addressed by substantially increasing buccal pressure rather than breathing frequency. Other researchers, however, have reported increases in respiratory rates during recovery (e.g., Kraiukhin and Smirnova 1966; Kynard and Lonsdale 1975). Respiratory failure in eels, and perhaps certain other fishes, can also be caused by a suffocating excess of mucus produced on the gills while under the influence of an electrical field (Lamarque 1990).

Stunned fish should be quickly removed from the electric field and placed in an uncrowded tank or pen with fresh, well-oxygenated water for recovery. Chmielewski et al. (1973) noted that a trout not breathing for 5 min had little chance of survival without artificial respiration (e.g., moving fish back and forth or otherwise pumping or forcing fresh, oxygenated water over the gills). Based on experiments with brown trout, they reported that re-establishment of equilibrium and normal respiratory movements usually required under 1 to 2 min and that recovery time increased with field intensity and fish length but decreased with successive exposures (suggesting decreased sensitivity to the field). Northrop (1967) noted that recovery from AC-induced electronarcosis (tetany?) is relatively slow, taking as long as 5 to 10 min for some larger species. Schreck et al. (1976) noted a similar "apparent" recovery time for yearling hatchery-reared rainbow trout subjected to 230-V, 2.3-A, DC in water with a temperature of 13°C and conductivity of 227 μS/cm. In experiments with 5- to 9-cm TL common shiners (*Luxilus cornutus*), Adams et al. (1972) narcotized fish by 5- to 30-s exposures in homogenous fields of 62- to 145-V DC (~ 1.5-3.6 V/cm) and found that recovery times increased with field intensity, exposure time, and length of the fish; shiners requiring over 2 min for recovery frequently died.

Stress and fatigue are physiological responses that usually require only a short time for recovery (fractions of an hour to less than a day). But some species are so sensitive to certain stresses that recovery can take weeks or months (e.g., handling and confinement stresses in some sharks—Smith 1991). In some cases stress can be so great, or fish so sensitive, that the fish eventually die.

Stress disrupts osmoregulatory functions and normal behavior. In response to tetany in a DC field, Schreck et al. (1976) reported immediate increases in blood concentrations of plasma corticoid (adrenal hormones, steroids), lactate or lactic acid (byproduct of anaerobic muscular activity), and thrombocytes (white blood cells instrumental in blood clotting) in yearling hatchery-reared rainbow trout. Increases in thrombocytes might be at least partially a response to tissue trauma, minor bleeding, or perhaps even hemorrhages. Blood glucose exhibited a delayed response, not increasing significantly until after lactic acid levels returned to normal, about 3 h after being tetanized. Schreck et al. (1976) found no immediate effect on blood levels of packed cells (Hematocrit), plasma protein, calcium, magnesium, or androgen. Nor did they find any effect on electrophoretic patterns of 13 tested isoenzyme systems (proteins often used in systematic analyses). Burns and Lantz (1978) reported similar results for lactate, hematocrit, and plasma protein in adult largemouth bass (*Micropterus salmoides*). They also tested for electrofishing effects on hemoglobin concentrations in the blood and the percentage of water in muscle tissue but found no differences from control fish or changes during a 19-h period after electrofishing. Contrary to these results, Bouck and Ball (1966) reported that plasma protein concentrations (and composition) in rainbow trout, was affected by electrofishing, as well as seining and hook and line. Because of the effects of electrofishing on blood chemistry, the U.S. Environmental Protection Agency recommended that electrofished specimens not be used in physiological or bioassay studies (Weber 1973 according to Emery 1984).

All capture methods are stressful to some degree (Wydoski 1980). Schreck et al. (1976) concluded that stress induced by electrofishing is similar to that caused by hypoxia and extreme muscular activity. Stresses can be cumulative; if electrofishing stresses are added to existing environmental stresses (e.g., pollution), mortality might increase significantly (Wydoski 1980). Increased mortality can occur directly as a result of stress and fatigue or indirectly through greater susceptibility to predators, disease, and parasites. In some cases, delayed, stress-related mortality can be a more significant concern than immediate electrofishing mortality. Injury-related stresses may persist for long periods of time. Such long-term stresses would likely affect the fish's physiology, behavior, growth, and reproduction.

Mortality, stress, and some injury can be as much a result of handling after capture (especially improper or careless handling) than of electrofishing itself (Hudy 1985; Barrett and Grossman 1988). According to Vibert (1967b), Halsband reported that the average duration of residual effects after removal from the current is 20 min for exponential (capacitor- or condenser-discharge) PDC, 60 min for DC, and 120 min for AC. But Kolz and Reynolds (1990b) noted that oxygen debt can take hours to pay back, and Schreck et al. (1976) concluded that full physiological recovery of electrofished specimens requires more than 6 hours (about 24 hours according to Whaley et al. 1978). This amount of holding time is unreasonable for most field operations, and because stress can also be induced by confinement, fish should probably be released as soon as possible after recovering their equilibrium and normal respiration. Earlier release might make them especially easy prey for predators (Whaley et al. 1978). Waiting until after equilibrium and respiration are adequately re-established also allows more opportunity to observe, document, and aid hurt or distressed specimens. If undesirable effects are observed, electrofishing procedures should be adjusted to minimize those effects. Emery (1984) suggested adding salt (1.5%) to the holding water to help fish replace lost ions. He also suggested adding a light anesthetic, e.g., MS-222, to reduce additional stress. However, if the anesthetic slows recovery of respiration in fish that have been tetanized, it might do more harm than good. Eloranta (1990) reported that recovery of electrofished specimens was slower and mortality (70-80%) significantly higher in unaerated containers treated with MS-222 than in containers without MS-222.

Electrofishing also affects fish behavior. Mesa and Schreck (1989) reported that in an artificial stream, rates of feeding and aggression decreased in both hatchery-reared and wild cutthroat trout immediately after they were electrofished and marked. In a natural stream, Mesa and Schreck (1989) observed that similarly electrofished and marked wild trout immediately sought cover, remained relatively inactive, did not feed, and were easily approached by a diver. An average of 3-4 h was required for 50% of the fish to return to normal behavior. In contrast, fish that remained uncaptured in the same section of the stream, even after successive passes, exhibited little change in normal behavior. Either uncaptured fish were insufficiently affected by the electric fields, or handling and marking of captured fish were responsible for the effects on behavior. Horak and Klein (1967) experimented with rainbow trout and found that swimming performance was significantly reduced in fish captured by electrofishing. Fatigue from long exposure or high intensity fields can also reduce a fish's near-term sensitivity to subsequent exposures (Chmielewski et al. 1973). Cross and Stott (1975) suggested that electrofished specimens might be less catchable for the next 3 to 24 h and that this response could substantially affect population estimates based on short-term mark-recapture or depletion techniques.

Spinal and Related Injuries

Hauck (1949) provided perhaps the most detailed description of electrofishing injuries. In a rescue attempt, 503 rainbow trout (0.7-2.3 kg), were electrofished from a canal in Idaho using hand-held electrodes and a portable (truck-mounted), 110-V, 60-Hz, 495-W AC generator. Voltage was set by rheostat at 80 to 90 V, just enough to momentarily stun fish within 3 m of the electrodes. Hauck noted that reactions of fish in the field varied. Respiratory activity increased in all fish and most fish experienced at least partial muscular paralysis. Fish exhibiting partial paralysis swam in an arc around the electrode (oscillotaxis?), whereas those exhibiting total paralysis (tetany, including cessation of respiratory movements?) would float momentarily on their sides then sink slowly to the bottom.

Hauck described the injuries in captured fish as follows: "A number of fish hemorrhaged from the gills or vent, or both. Others showed dilated and hemorrhaged blood vessels in the skin near the vent. Several were observed with the intestine protruding from the vent. Physical contact with the electrode caused the appearance of dark vertical bars on that area of the fish which touched the electrode."

The fish were transported to a nearby hatchery pond where they were observed for 2 to 5 d before release. During this time, 131 fish (26%) died either as a result of electrofishing or subsequent handling. Although not stated, incidence of injury was probably much higher than mortality (Reynolds and Kolz in Reynolds et al. 1988). Hauck noted that: "Paralysis of swimming muscles persisted in some fish for several days. This loss, or partial loss, of locomotion would indicate an injury to the nervous system. The dark, vertical bars remained in evidence. Dead or dying tissues in the caudal peduncle and caudal fin appeared on several fish which fact would indicate loss or impairment of circulation to this region. Several fish lost their sense of balance."

Hauck (1949) dissected 10 specimens with representative injuries from among the rescued fish. "One 5-pound rainbow trout had a fractured sixth caudal vertebra. As a result of this fracture the haemal artery and vein had ruptured in the seventh caudal vertebra. The breakdown of circulation of blood at this point caused the death of the entire body posterior to the injury, including muscles and skin. Blood clots and hemorrhaging were evident throughout the caudal peduncle, particularly in the region adjacent to the fracture. This fish suffered total paralysis of the swimming musculature before its death."

"A 1.5-pound specimen had three fractured vertebrae, the 11th, 29th, and 30th abdominals. Curvature of the spine appeared through the abdominal vertebrae 18 to 22, and the ligamentous connections between ribs and parapophyses in this region were broken. This fish also had blood clots in the afferent branchial arteries and had hemorrhaged through the membranes of the gill filaments."

He described four more of the 10 fish as having fractured vertebrae and (or) spinal curvature which he described as ligamentous fractures. One of these fish had 12 ruptured dorsal (segmental?) arteries anterior to a fracture in a single abdominal vertebra. Another, which had an impaired sense of balance before it was killed, had bloody fluid in the semi-circular canals. Six of the 10 fish had suffered injury in the region of the brain as evidenced by dilated blood vessels or blood clots. Hauck suggested that the latter brain injuries might have been secondary to electrofishing, perhaps caused by collisions with rocks or other structures. He concluded his 1949 publication with the suggestion that further investigations on the injurious effects of electrofishing were needed before the technique was employed too widely in fishery management.

Nature of the Injuries

Compressed, broken, or misaligned vertebrae and related electrofishing injuries including separated or damaged ribs, damaged swim bladders, ruptured dorsal and haemal arteries, and other internal hemorrhages (Figures 13, 14, 15) are believed to be caused by momentary but powerful convulsions of the body musculature. Bleeding at the vent could be caused by related damage to the viscera, but bleeding at the gills is probably a separate phenomena. Lamarque (1990) suggested that such convulsions are the result of direct excitation of the muscles (via motor nerves?) and "hyper-reflexivity." Sharber et al. (unpubl. ms. 1991; also Sharber pers. commun.) believe that they represent "random seizures" similar to those sometimes experienced by people with

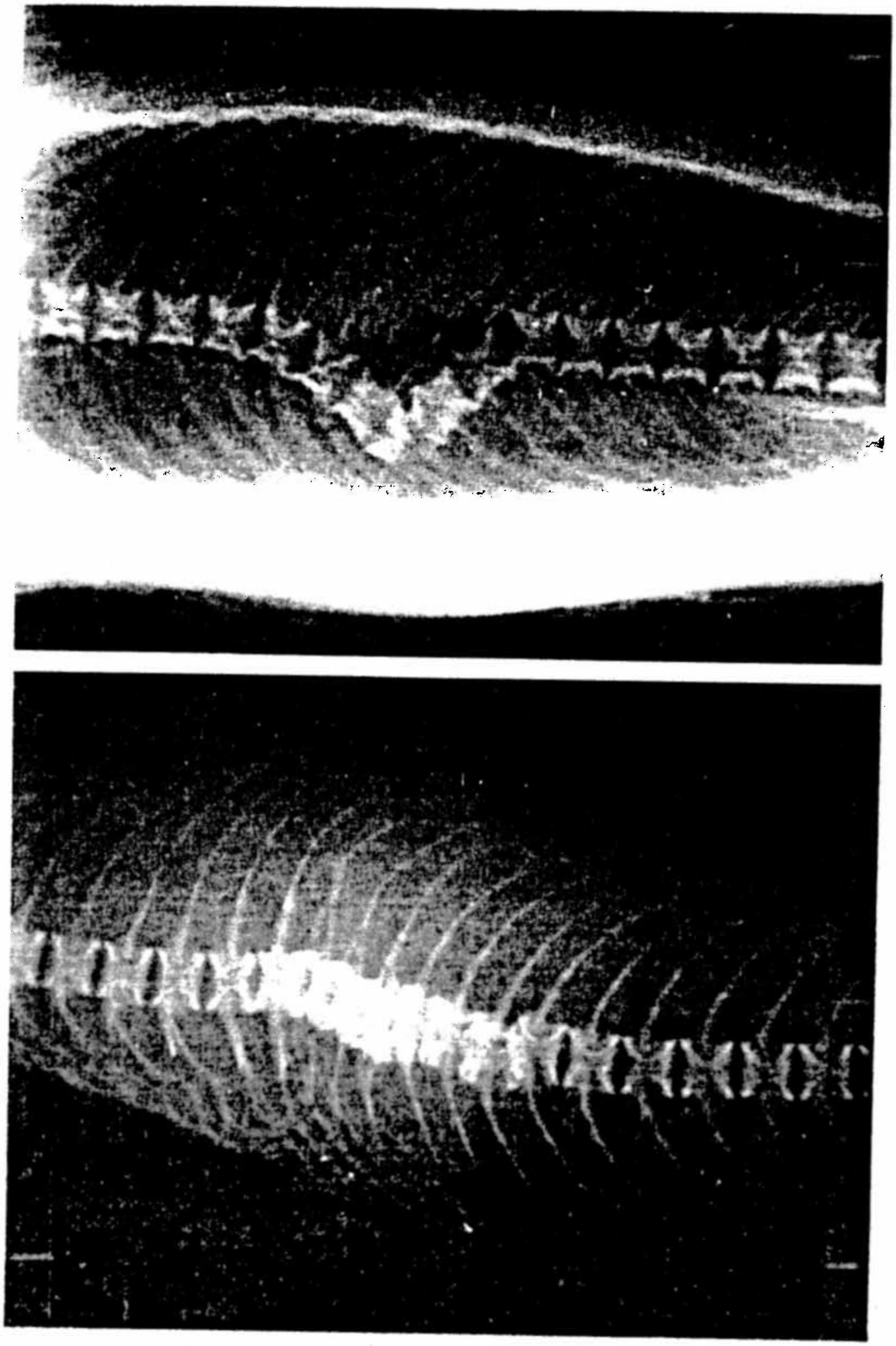

Figure 13. Dorsal-view (top) and lateral-view (bottom) X rays of the same spinal misalignment and fractured vertebrae in an electrofished rainbow trout. (Photographs provided by and reproduced with the permission of N. G. Sharber).

epilepsy or subjected to electroconvulsive therapy before chemicals were available to block electrical stimulation of motor neurons.

These myoclonic jerks or seizures are believed to occur simultaneously, or nearly so, on both sides of the body, thereby subjecting the vertebral column to opposing forces which can break, crush, or dislocate the vertebrae (Lamarque 1990; Sharber pers. commun; Sharber et al. unpubl. ms. 1991). Stewart (1967 according to Lamarque 1990) reported that spinal injuries by DC (PDC?) are primarily compression fractures whereas those produced by AC are primarily misalignments. However, in PDC, Sharber and Carothers (1988, 1990) and Fredenberg (1992) observed both forms of vertebral damage. Fredenberg (1992) also noted rare occurrences of misalignments in (rippled) DC. Comparing DC and several PDC currents, Fredenberg (1992) concluded that there were no notable differences in the types of injuries caused by the various currents, only differences in their frequency and severity.

Electrofishing-induced vertebral damage is usually accompanied by ruptured blood vessels, torn muscles or ligaments, and perhaps other soft-tissue damage (Hauck 1949; Taylor et al. 1957; Spencer 1967; Sharber and Carothers 1988, 1990; Holmes et al. 1990; Wyoming Game and Fish Department 1990; Fredenberg 1992). However, Holmes et al. (1990) and Fredenberg (1992, pers. commun.) occasionally observed hemorrhages along the spine or in the musculature without apparent corresponding damage to vertebrae. Sometimes the incidence of

Figure 14. Hemorrhage and associated tissue and vertebral damage in an electrofished trout as revealed by necropsy. (Photograph provided by and reproduced with the permission of N. G. Sharber).

such hemorrhages was far greater than the incidence of fish with obvious vertebral damage. To a lesser extent, the reverse situation, vertebral damage without associated hemorrhages, was also observed. Fredenberg (1992) noted that when only hemorrhages or only damaged vertebrae were detected, the injury was usually minor to moderate.

Electrofishing-induced spinal injuries can occur anywhere along the spinal column, including immediately behind the head, but most are observed near or beyond the midpoint of the spine. Predominant location of these injuries varies with species. Injuries to Salmoninae are most frequently located near or between the dorsal and pelvic fins (Sharber and Carothers 1988, 1990; Fredenberg 1992), whereas those to centrarchids and ictalurids are predominately located in the caudal region, posterior to the vent (Spencer 1967). The number of vertebrae involved in each incident varies considerably from one to as many as 20 depending on species and severity of the injury. Fredenberg (1992) found misalignments to typically involve two to five vertebrae in the midst of a larger series of compressed vertebrae.

Over 60% of injured fish examined by Fredenberg (1992) and his associates were characterized by two or more hemorrhages with up to eight in one specimen. Multiple, well-spaced, vertebral injuries were also common. Multiple hemorrhages frequently alternated from side to side, sometimes in evenly spaced patterns. Explanations for multiple injuries, especially one-side-only and alternating hemorrhages, have yet to be explored. If multiple injuries are the result of multiple, temporally separated seizures and all myomeres contract simultaneously, it would be logical to expect the weakest portion of the spine, that already injured, to be most susceptible to subsequent injury rather than other portions of the spine. However, multiple injuries might be likely if the nerves associated with

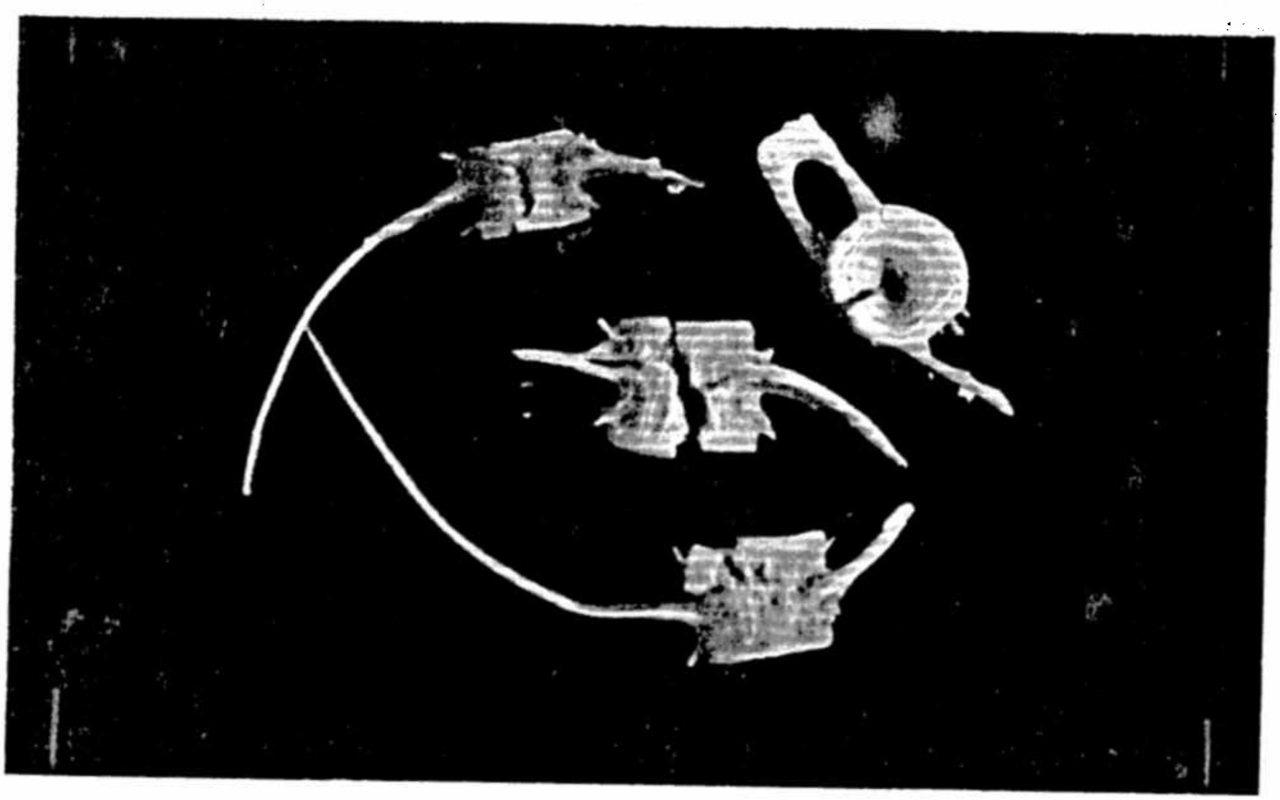

Figure 15. Fractured vertebrae from an electrofished rainbow trout. (Photograph provided by and reproduced with the permission of W. A. Fredenberg).

the original injury were also damaged or otherwise made, at least temporarily, non-functional (no longer subject to stimulation or over-stimulation). If multiple injuries result from single convulsive events, perhaps the muscular contractions sometimes differ in strength or intensity on each side of the body or in various regions of the body. Perhaps they pass along the body as longitudinal waves. We have much to learn about the causes and mechanisms of electrically induced spinal and related injuries.

Detection and Evaluation of the Injuries

Bent or curved backs, bleeding, or brands may be obvious signs of internal injuries, but such external signs of spinal and related internal injuries are often absent. Injured specimens often look and behave normally. When external manifestations are present, they usually indicate that internal injuries are relatively severe.

Brands may result from direct contact with or close proximity to the electrode, but as noted earlier, such marks also appear on fish netted some distance from an electrode (Lamarque 1990). Although Lamarque (1990) noted that some brands may be true burns resulting from direct contact with an electrode; he, Emery (1984), and Fredenberg (1992) believe that most brands are discolorations of the skin due to the dilation of skin melanophores, possibly as a result of sympathetic nerve damage or stimulation. Reynolds (unpubl. ms. 1992) agreed that at least the blotchy, irregular-shaped, marks are probably temporary intensifications of dermal pigment. But Reynolds (unpubl. ms. 1992) also suggested that some dark marks, particularly the anterior-pointing, V-shaped marks, are hemorrhages in or under the skin caused by the ruptured capillaries of injured muscles. Perhaps some blood seeps from internal hemorrhages along the myosepta to under the skin. Most brands, especially pigmental brands, tend to be ephemeral. They rapidly dissipate after death (Fredenberg 1992) and vanish within 4 days, perhaps much sooner, on living specimens (Holmes et al. 1990). Although these marks are collectively best described as "bruises", the term "brands" is more widely accepted and will continue to be used in this report.

Brands effectively approximate the location of damaged vertebrae or associated tissues (Lamarque 1990; Fredenberg 1992). Even 25 years ago, Horak and Klein (1967) recognized internal hemorrhages and possible vertebral injuries as the cause for such marks. Lamarque (1990) suggested that if a large part of the body becomes dark, a total rupture of the spinal column is probable. In one sample of 152 electrofished rainbow trout, Fredenberg (1992) reported that 26% had brands and all but one of these branded fish were found upon X-ray analysis or necropsy to have spinal injuries. However, among the unbranded fish in the sample, another 37% were determined to have spinal or related tissue damage, bringing the total with such injuries to 63%. Among the injured fish, the incidence of more severe injuries was much greater among the branded than the unbranded fish (64% versus 17%). Horak and Klein (1967) found brands on 39% of the hatchery-reared rainbow trout they electrofished; extrapolating from Fredenberg's (1992) observations, far more of their fish were probably injured. Krueger (pers. commun.) observed that over 50% of rainbow and brown trout he electrofished for contaminants analysis had brands posterior to the dorsal fin. Many of the trout he subsequently dissected had damaged spines and most of these also had brands. McMichael and Olson (unpubl. ms. 1991) also reported a positive relationship between incidence of branding and spinal injury on electrofished hatchery rainbow trout and spinal injuries.

Except when particularly severe, spinal and related internal injuries often can only be detected or positively verified by X ray or necropsy (Sharber and Carothers 1988, 1990). Necropsies may be necessary to support the interpretation of X-ray analyses and detect related tissue injury and hemorrhages, some of which might not correspond to obvious vertebral damage (Fredenberg 1992). Fredenberg (1992) observed that most of the less severe hemorrhages were visible only on one side of the spine and suggested that necropsy procedures should include filets of both sides.

Based on their own experiments and observations, McCrimmon and Bidgood (1965) stated that unless X rays are also taken prior to electric-field exposure, vertebral damage caused by electric fields might be difficult to distinguish from previous anomalies. They documented such prior anomalies in up to 16% of rainbow trout electrofished from Great Lakes tributaries in Ontario. All anomalies were compacted segments of the spine usually

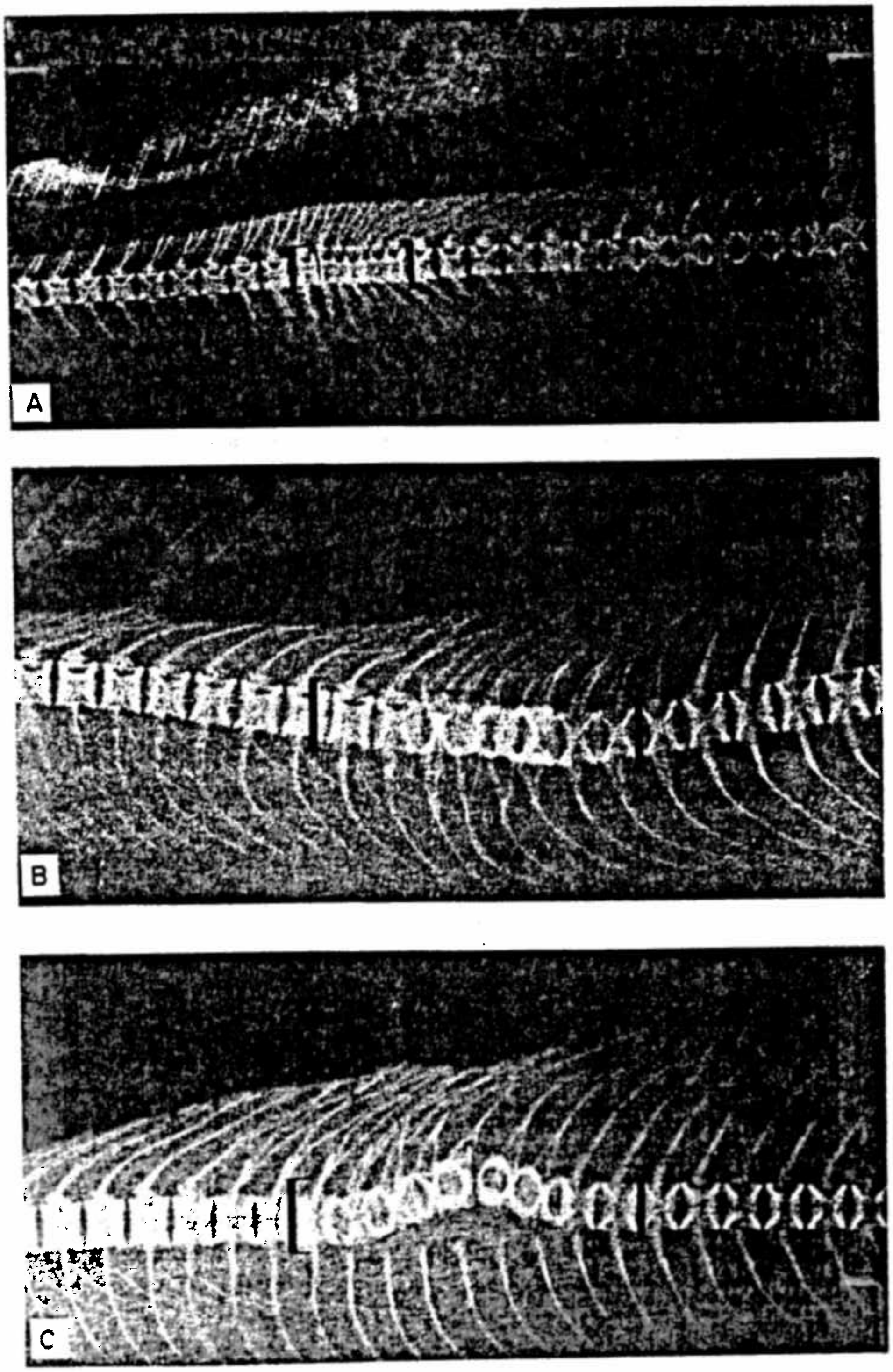

Figure 16. X rays of spinal anomalies in rainbow trout (reproduced with permission from Sharber and Carothers 1988, Figure 1). A represents a natural anomaly; B, an old injury; and C, a new electrofishing-induced injury.

involving four to nine vertebrae between the dorsal and pelvic fins; no significant curvature or misalignment was noted. The affected vertebrae were typically 60 to 75% shorter than normal vertebrae and, at least in fish that were dissected, fused and immobile. Sharber and Carothers (1988) stated that McCrimmon and Bidgood could not determine the cause of the abnormalities, but indeed, the authors concluded that these anomalies were probably of natural origin (genetic or developmental) and definitely not electrofishing injuries. Gill and Fisk (1966) X rayed nearly 20,000 fish and documented "natural" (genetic or environmental) vertebral abnormalities in 0 to 11% of the fish in samples of wild, adult pink, sockeye, and chum salmon (*O. keta*). Gabriel (1944 as cited by McCrimmon and Bidgood 1965) similarly documented vertebral abnormalities in 2 to 3% of the mummichog (*Fundulus heteroclitus*) he examined from natural populations. As in McCrimmon and Bidgood's (1965) trout, most of these abnormalities were foreshortened and fused vertebrae; misalignments were not reported and therefore are assumed not to have been observed.

Sharber and Carothers (1988, 1990) also suggested that naturally occurring spinal anomalies would appear dense (compressed) and fused in X rays, but countered that electrofishing-induced damage can be distinguished by separation and notable misalignment of vertebrae. They also implied with an illustration (photographs of X rays) that old injuries could be distinguished from both natural anomalies and recent injuries but did not discuss criteria (Figure 16). Fredenberg (1992) noted that in X rays, old electrofishing injuries are evidenced by heavy calcification and fusion and usually distinguishable from natural anomalies by vertebral misalignment. Still, interpretations of the cause of such anomalies or injuries must be made with care. As documented by McCrimmon and Bidgood (1965), Gabriel (1944 as cited by McCrimmon and Bidgood 1965), and Gill and Fisk (1966), natural occurrences of spinal anomalies, especially compressions, may be common in some wild or cultured populations. Also, lordosis (dorso-ventral bends or misalignments), scoliosis (lateral bends or misalignments), or vertebral compressions can result from abnormal development, nutritional deficiencies, pollutants, or injury caused by accidents, parasites, predators. Spinal injuries can also be caused by other gear (Holmes et al. 1990) or careless handling by field personnel. Apparently, even fresh hemorrhages that are relatively minor cannot always be attributed to electrofishing. Fredenberg (1992) found some lateral, intervertebral, and especially subvertebral hemorrhages in control fish. Comparable evaluation of the incidence of spinal injuries and anomalies among "control" fish that are not electrofished is recommended to determine background levels of such occurrences and assist in the interpretation of injuries and anomalies in electrofished specimens. In controlled experiments where individual fish can be identified, McCrimmon and Bidgood's (1965) suggestion of pretreatment X rays should be seriously considered.

Participants of a special session on electrofishing injuries at the June 1991 Western Division AFS meeting (Bozeman, Montana) considered, modified, and agreed upon a set of procedures and criteria recommended by J. B. Reynolds for standard documentation of the presence and severity of damage to the spine and associated hemorrhages. The agreed upon version was included in a manuscript by Reynolds (unpubl. ms. 1992) for publication in the AFS bulletin *Fisheries*; it is reproduced herein as Table 4. By the recommended criteria, vertebral damage (usually based on X rays) and hemorrhages (based on fillets of muscle tissue along the spine) are separately ranked from zero to three according to severity. Fredenberg (1992) used the criteria and reported that despite cases in which hemorrhages were observed without corresponding identification of vertebral damage, and vice versa, severity ratings for damage to the spine and hemorrhages in associated tissues were reasonably similar and severe injuries were nearly always detected as such by both criteria. Although Reynolds' recommended procedures specify only lateral-view X rays, it might be useful to take both lateral- and dorsal-view X rays to facilitate interpretation of the nature and severity of spinal injury (Figure 13).

Relationship Between Injury and Mortality

Spencer (1967) found no relationship between the incidence of spinal injuries and immediate mortality in his experiments with bluegill (*Lepomis macrochirus*). Many bluegill killed by electricity had

Table 4. Procedures and criteria for documenting damage to the spine and associated hemorrhages (reproduced with permission from Reynolds unpubl. ms. 1992, Table 2).

Internal Hemorrhage

Fish should be killed within 1 h after capture and either frozen or held on ice to allow clotting in blood vessels. Fish should not be filleted immediately after death because fillet-related bleeding will mask injury-related hemorrhages. Fillets should be smoothly cut close to rays and spine, through the ribs and back to the caudal peduncle. Rate the injury from the actual specimen; then photograph the worst side of fish with the fillet inside up (color slides are best for follow-up evaluation). Rate the worst hemorrhage in the muscle mass as follows:

0 - no hemorrhage apparent

1 - mild hemorrhage; one or more wounds in the muscle, separate from the spine

2 - moderate hemorrhage; one or more small (≤ width of two vertebrae) wounds on the spine

3 - severe hemorrhage; one or more large (> width of two vertebrae) wounds on the spine

Spinal Damage

Fish should be dead or anesthetized to insure good resolution on X-ray negatives. Photograph the left side of each fish, positioning it to include all vertebrae. X-rays of two or more fish per plate will save money. Record the position of every affected vertebra, counting the first separate vertebra behind the head as number 1. Rate the worst damage to the spine as follows:

0 - no spinal damage apparent

1 - compression (distortion) of vertebrae only

2 - misalignment of vertebrae, including compression

3 - fracture of one or more vertebrae or complete separation of two or more vertebrae

no spinal injuries whereas many of the survivors did. Hudy (1985) similarly found that among trout with electrofishing-induced injuries nearly 90% survived, but over half the injured survivors continued to exhibit abnormal swimming behavior or brands 15 d after the electrofishing event. Based on another experiment with a very small number of channel catfish, Spencer (1967) concluded that many spinal injuries heal completely. After 45 d, even catfish with externally obvious spinal deformities appeared to swim normally. Taylor et al. (1957) concluded, based on limited evidence, that the primary cause of electrofishing mortality is physiological and only occasionally due to physical injuries.

Factors Affecting Injuries, Mortality, and Other Adverse Effects

Type of Current

AC—For its reputation, there is amazingly little published data on mortality caused by AC electrofishing (Table 3). DeMont (1971 according to Emery 1984) reported approximately 60% mortality for threespine stickleback (*Gasterosteus aculeatus*) electrofished with AC versus 50% for those subjected to DC (possibly PDC, details of the study were not reported by the secondary source). These figures were cumulative for 5 d following the electrofishing event but most deaths occurred during the first day. Using 110-V AC, Pratt (1955) reported mortality of 4% for rainbow trout (mean length 19 cm), 10% for brook trout (mean length 25 cm), and 20% for brown trout (mean length 20 cm) electrofished in hatchery raceways with a water conductivity of 308 µS/cm. [As in many subsequent references, the author did not indicate whether lengths were total, fork, or standard lengths; unless overlooked, such is indicated in this report when given by the source.] By comparison, he reported substantially lower mortality, only 2, 0, and 4%, respectively, when using 230-V DC. Except for the report of 26% mortality by Hauck (1949, discussed earlier), most remaining reports of mortality when using AC are quite low. For example, Taylor et al. (1957) reported 4.2% mortality among rainbow trout exposed to 60-Hz AC at voltage levels beyond those required for narcosis. Under comparable conditions, mortality for PDC and DC were only 0.3% and 0.0%, respectively. The authors noted that they observed a similar trend in mortality for these currents when electrofishing in natural streams.

Hudy (1985) found less than 1 to 3% mortality among 2,250 hatchery rainbow trout (16-26 cm) and brook trout (12-24 cm) electrofished with 350- to 760-V, 250- to 300-Hz AC. However, the electrofishing took place in concrete raceways with a water temperature of 5.5°C and conductivity of 10 µS/cm, which combined with the type and size of hand-held electrodes used probably resulted in relatively small, low-intensity fields (Sharber *in* Sharber and Hudy 1986).

Schneider (1992) monitored delayed mortality of warmwater and coolwater fish he collected from Michigan lakes and ponds (conductivities of 66 to 520 µS/cm) with a 230-V, 3-phase AC boat electrofishing system and a 3.8 m by 3.3 m array of five boom-mounted electrodes. Output was adjusted such that large fish recovered within 30 s but was high enough to stun small as well as large fish. He concluded that (3-phase) AC electrofishing did not measurably increase the mortality of the fishes studied: yellow perch (*Perca flavescens*), bluegill, pumpkinseed (*Lepomis gibbosus*), green sunfish (*Lepomis cyanellus*), lake chubsucker (*Erimyzon sucetta*), and golden shiner (*Notemigonus chrysoleucas*). Little or no mortality was observed among fish held 1 to 4 d, 0 to 10% among fish held 10 d, 0 to 12% among fish held 22 to 31 d, and 0% and 94% for fish held for 38 and 40 d, respectively. The high mortality for fish held 40 d was believed to be due to handling and high-temperature conditions rather than electrofishing.

Among the specimens he electrofished and monitored for delayed mortality, Schneider (1992) reported externally obvious injury only to a group of 53 yellow perch—accumulations of bright-red blood in the sinus venosus near the base of the gills. The blood dispersed within a day, and all fish survived and appeared in good condition at the end of their respective holding periods. None of the fish he monitored were X rayed or dissected. Schneider also explicitly stated that he rarely observed external indications of injuries among thousands of fish he had collected with AC.

In addition to the relatively low incidence of mortality he reported, Hudy (1985) also reported less than 3% spinal injury and other abnormalities among the 2,250 hatchery rainbow trout and brook trout he electrofished with AC in very cool, low-conductivity waters. Based on X rays, all spinal injuries were described as fractures and dislocations. Hudy also observed some fish in each treatment with fused vertebrae, but assumed that these anomalies were not caused by electrofishing; he made no mention of compressed, unfused vertebrae. If he overlooked or confused compressed vertebrae with natural anomalies, the actual number of injuries would probably have been higher, especially among normal-appearing survivors. Hudy concluded that the relatively low percentages of mortality and injury he observed would probably be acceptable for most management purposes and that with proper caution (effects on other life stages, sizes, and species unknown) high-voltage AC electrofishing could effectively be used in low-conductivity waters.

McCrimmon and Bidgood (1965) reported no skeletal damage attributable to either 60-Hz AC or 120-Hz, half-sine PDC fields among 80 hatchery rainbow trout (11-26 cm TL) that were exposed in the laboratory or among 291 wild rainbow trout (6-59 cm TL) that were electrofished in Ontario streams tributary to the Great Lakes. For the laboratory studies, water conductivities were 475 to 550 "μv" (μS/cm?) and temperatures 11 to 13°C. All fish were X rayed (the hatchery fish before and after exposure) and some were dissected. Up to 16% of the fish, depending on the stream, had spinal compressions, but among specimens also examined by necropsy the compressed vertebrae were fused, immobile, and, therefore, not considered electrofishing injuries.

Contrary to the above reports, Hollander and Carline (1992) and Spencer (1967) documented substantial incidence of spinal injury for fish exposed to AC. Hollander and Carline (1992) electrofished brook trout (9-24 cm TL) in small, low-conductivity, streams and subsequently examined them by X ray and necropsy. He found hemorrhages and (or) spinal damage in 26% of the trout collected with AC and 22% in those collected with PDC. In controlled experiments, Spencer (1967) compared the frequency of vertebral damage induced in bluegill by selected AC and DC currents for various lengths of exposure. Based on dissection of the tested fish, he consistently observed more injuries in fish exposed to AC fields, 9 to 16% for 230-V, 3.1-A AC (3-phase, 180 Hz) and 3 to 7% for 115-V, 2.0-A AC versus 0 to 3% for 115-V, 1.9-A DC (rectified AC, rippled DC). In another test, at least 60% of 10 channel catfish subjected to 230-V AC suffered spinal injuries.

DC—As discussed earlier, DC is considered by most electrofishing authorities to be the current least fatiguing to fish and least dangerous to both fish and researchers. But even under conditions of relatively smooth DC (small ripples), fish mortalities have been observed (Table 3). Lamarque (1967a, 1967b, 1990) purposely exposed trout to various currents for 20 s at a distance of 20 cm from the anode. He reported mortalities of 6 and 17% for two forms of DC and 50 to 93% for four PDC waveforms. Taylor et al. (1957) reported no mortality for trout electrofished with DC (mortalities for AC and PDC were 4.2% and 0.3% respectively). Barrett and Grossman (1988) monitored for a month the survival of mottled sculpin (*Cottus bairdi*) and several small cypriniform fishes collected by DC electrofishing and kick-seining in a cool, low-conductivity (10-15 μS/cm) stream. They reported no significant differences between gear in delayed mortality (0-12% for the electrofished specimens). In a similar experiment, mottled sculpin were electrofished and handled weekly for 4 weeks but again there were no significant differences between mortality of electrofished (45-50%) and control (35-60%) fish. Barrett and Grossman (1988) concluded that most of the mortality was probably due to handling stress and that DC electrofishing in low-conductivity streams has little effect on the short-term survival of mottled sculpin. As noted above for AC, DeMont (1971 according to Emery 1984) reported approximately 50% delayed mortality (mostly within the first day) for threespine stickleback electrofished with DC (possibly PDC?) versus 60% for AC. Eloranta (1990) reported acute mortalities greater than 50% for burbot (*Lota lota*) collected in low-conductivity (40-60 μS/cm) littoral zones of a lake with 450- to 650-V DC (0.5-1.3 A); for most other species, mortalities were less than 11%. Deaths were greatest when operating at over 600 V.

Like mortalities, spinal injuries are also typically lower for DC than AC or PDC. Spencer (1967) found substantially less spinal injury among bluegill subjected to DC, 0 to 3%, than AC, 3 to 16%. Fredenberg (1992), who tallied the results of both X rays and necropsy, including minor hemorrhages, reported incidence of spinal injury with DC as high as 30% for rainbow trout and 10% for brown trout, but these figures were still much less than he observed with PDC (up to 98% for rainbow trout). Taube (1992 according to Reynolds et al. 1992) documented much less injury among hatchery rainbow trout electrofished with DC and Coffelt's *CPS* (< 18%) than among trout electrofished with 20- to 60-Hz PDC (40-60%). McMichael et al. (1991) and McMichael and Olson (unpubl. ms. 1991) found that spinal injuries for rainbow trout in DC increased with voltage output (4% at 300 V and 17% at 400 V), but again these percentages were substantially less than for PDC (35-53%).

Fredenberg (pers. commun.) compared the incidence of injury among adult rainbow trout, mountain whitefish, and suckers (white sucker, *Catostomus commersoni*, and longnose sucker, *Catostomus catostomus*) using three currents reputed to be least damaging to fish: DC (maximum output of 110 V, 5 A), 15-Hz PDC (200 V, 17.5 A), and Coffelt's *CPS* (400 V, 22.5 A). The fish were collected in October 1990 by electrofishing boat (cable electrodes) in the Missouri River (about 10°C and 450 µS/cm). Approximately 50 specimens for each species-current combination were sacrificed and examined by necropsy for injuries to the spine and hemorrhages along the spine or in the musculature; the fish in each species-current group averaged 38 to 42 cm in total length. For rainbow trout, DC resulted in injuries to the spine of 6% percent of the fish, far less than observed for 15-Hz PDC (20%) but slightly higher than observed for *CPS*. Few, if any, injuries to the spine were observed for mountain whitefish or suckers (0-2%), regardless of the current. However, when the percentage of fishes with these injuries were combined with the percentage of fishes with hemorrhages only (all considered minor according to Reynolds' criteria–Table 4), the percentage of mountain whitefish injured increased to 6% for DC, 20% for 15-Hz PDC, but just 2% for *CPS* (all minor hemorrhages). Interestingly, for the suckers, DC produced the greatest percentage of total injuries, 18%. By comparison, 15-Hz PDC produced 10% and *CPS* only 4% total injuries among the suckers.

Lamarque (1990) noted that damage can occur in DC when a fish lies motionless and tetanized near the cathode or when the current is abruptly re-established. In the latter instance, he suggested that DC would be momentarily acting like PDC but at a higher voltage than would be needed for narcosis in PDC (beyond reactive detection, the thresholds for comparable responses are higher in DC than PDC).

PDC—Generally, mortalities reported for PDC are less than those reported for AC but similar to or greater than those reported for DC (Table 3, above discussions for AC and DC). But this does not appear to be the case for spinal injuries. The only reported comparison of AC and PDC injuries (Hollander and Carline 1992) concluded that the incidence of spinal injuries was similarly high for both currents (26% and 22%, respectively for brook trout 9-24 cm TL). Comparisons between PDC and DC reveal that the incidence of spinal injuries for PDC is often substantially higher than for DC, depending on the PDC waveform and frequency selected.

As noted above for AC, McCrimmon and Bidgood (1965) exposed 371 hatchery and wild rainbow trout (6-59 cm TL) to 60-Hz AC and 120-Hz, half-sine PDC (full-wave rectified AC) electrofishing fields. For the laboratory studies, water conductivities were reported as 475 to 550 "µV" [sic, authors probably meant µS/cm] and temperatures as 11 to 13°C. Based on X rays and necropsies, no injuries or anomalies were attributed to either type of electric field, but significant numbers of previously existing spinal abnormalities, mostly compressions, were documented. In fish that were dissected, the vertebral compressions were fused and immobile. This report of no injury is in stark contrast to an ever-increasing number of field studies in which very substantial numbers of fish are injured with PDC.

Sharber and Carothers (1988, 1990) reported spinal and associated soft-tissue injuries in 50% (44-67% by waveform) of 209 large rainbow trout that were electrofished below Lake Powell in 1985 and 1986. The fish were frozen and later examined with X ray; 60 specimens were also examined by necropsy. The specimens measured 30 to 56 cm TL; smaller fish were not examined. The injuries (dislocations, fractures, or both) involved a mean of eight vertebrae and typically were located between the dorsal and pelvic fins. Spinal injuries were not found in 12 non-electrofished trout of similar size obtained from a hatchery (the trout fishery below Lake Powell is probably maintained by hatchery stock). The electrofished specimens were collected at night in water 1 to 3 m deep with temperatures of 10 to 11°C and conductivities of approximately 450 to 600 µS/cm (specific conductivities of 600-800 µS/cm at 25°C). The raft-mounted electrofishing system included a 6,500-W, 240-V, 60-Hz, single-phase AC generator, a Coffelt *VVP-15* variable-pulse generator for rectangular and quarter-sine waveforms, a *VectorMax 101* pulsator for exponential (capacitor-discharge) waveforms, an oscilloscope to calibrate the pulsators, and 30-cm diameter steel-sphere electrodes suspended from bow and stern booms. Both pulsators were operated at a peak output of 260 V DC (selected through observations of catch rate), 60 Hz, and 25% duty cycle (pulse widths of 4.2 ms). Reynolds and Kolz (in Reynolds et al. 1988), using a median conductivity value, calculated approximate voltage gradients and power densities of about 8.6 V/cm and 38,500 µW/cm^3 at the surface of the spherical anode, 0.5 V/cm and 130 µW/cm^3 at 0.5 m, and about 0.15 V/cm and 12 µW/cm^3 at 1 m from the anode. Captured fish were maintained in a Faraday-shield live well (Sharber and Carothers 1987).

Reynolds and Kolz (*in* Reynolds et al. 1988) reported that recent studies by the Alaska Department of Fish and Game corroborated Sharber and Carothers' (1988) findings. In a Kenai River investigation, 50% of 22 rainbow trout over 400 mm fork length (FL) suffered spinal injuries. The Alaskan investigators noted that injuries seemed more likely among trout captured within 0.5 m of the anode. In this case, water conductivity (50 µS/cm at 7°C) and current and power densities near the anode were much lower than in Sharber and Carothers' (1988, 1990) study (about 50 µA/cm^2 and 50 µW/cm^3 at 0.5 m from the anode), but voltage gradient was higher (about 1.0 V/cm at 0.5 m). As a result of Sharber and Carothers' (1988, 1990) work and its own studies, the Alaska Department of Fish and Game imposed a moratorium on the use of electrofishing in population studies of large trout until the problem is resolved (Holmes et al. 1990; Reynolds pers. commun., unpubl. ms. 1992).

Other studies also corroborate Sharber and Carothers' (1988, 1990) findings, as well as document a notably higher frequency of injury for PDC than DC. In controlled hatchery experiments, McMichael et al. (1991) and McMichael and Olson (unpubl. ms. 1991) reported spinal injuries for 35% and 53% of the rainbow trout he electrofished twice, 7 d apart, with 300-V, 30-Hz PDC and 300-V, 90-Hz PDC, respectively (both rectangular waveforms), but only 4% and 17% with 300-V DC and 400-V DC, respectively. In field experiments, Meyer and Miller (1991, unpubl. ms. 1991) and Wyoming Game and Fish Department (1991) reported average single pass injuries of 8% for rainbow trout exposed to 370 to 390-V, 40-Hz PDC and 13% for those exposed to Coffelt's *CPS* pulse train operated at 460 to 470 V. Multiple passes increased injuries to an average of 30% of the fish. With equipment that was not properly calibrated, they (Meyer and Miller 1990; Wyoming Game and Fish Department 1990) reported PDC injuries for 25 to 85% of the fish examined during the first year of their investigation. Fredenberg (1992) reported injuries in up to 98% of the rainbow trout electrofished with PDC and up to 30% with DC (these figures were based on the combined results of both necropsy and X rays and are somewhat higher than they would be for either technique alone; in most other studies, percent injury was based on only one of the two techniques). As noted above for DC, Fredenberg (pers. commun.) reported notably higher percentages of injuries (including minor hemorrhages) for rainbow trout and mountain whitefish collected with 15-Hz PDC than with DC or *CPS*; only for suckers was the percentage of total injuries greater with DC. Total injuries for *CPS* never exceeded 6%. If only fish with obvious injuries to the spine are considered, percentages for mountain whitefish and suckers were 2% using 15-Hz PDC and 0% using *CPS*, but for rainbow trout they were 20% and 2%, respectively. Taube (1992 according to Reynolds et al. 1992) reported 40 to 60% injury for hatchery rainbow trout subjected to 20- to 60-Hz PDC, but less than 18% injury in DC and *CPS*. In low-conductivity field trials, Taube also documented less spinal injury among trout electrofished with *CPS* than with DC, but capture rates were also lower.

As noted above under the discussion of major responses of fish in electric fields, anodic taxis under PDC appears to differ from that under DC (Lamarque 1990; Fredenberg pers. commun.). If the mechanisms responsible for taxis under PDC are indeed different from those under DC, perhaps they are also responsible, at least in part, for the greater incidence of spinal injuries often observed under PDC.

Field Intensity

The effect of field intensity on mortality was dramatically demonstrated by Lamarque (1967a, 1967b, 1990). Trout were exposed for 20 s at a distance of 20 cm and 50 cm from the anode using a variety of DC and PDC currents. At 20 cm, where field intensity was much higher, mortalities were observed with all currents (17-93%), but at 50 cm from the anode, mortality was observed for only one of the same six currents (27% Table 3). The importance of field intensity, however, was actually documented much earlier by other researchers. Collins et al. (1954) reported that mortality in YOY chinook salmon (*Oncorhynchus tshawytscha*, 5-11 cm) increased directly with increases in voltage gradient above a threshold of 3.5 to 4 volts/cm PDC in a water conductivity of about 48 μS/cm (experiments were conducted in a homogeneous field with a rectangular waveform). Pugh (1962) likewise reported that the harmful effects of PDC are associated with intense electrical fields. For AC fields, the effect of increased mortality with increased field strength was documented as early as the late 1920s by McMillan (1928) for young-of-the-year (YOY) salmon (*Salmo salar*?). Hudy (1985), on the other hand, compared the effects of electrofishing with 350-V, 700-V, and 760-V AC (250-300 Hz, 250 W continuous) on 2,250 hatchery rainbow and brook trout and reported very low mortalities (0.5-1.8%) with no statistically significant differences among voltage levels. However, Sharber (*in* Sharber and Hudy 1986) suggested that very low water conductivity and the type of electrodes used probably resulted in relatively small, low-intensity electric fields (except immediately next to the electrodes) and that few mortalities would be expected in such weak fields. Low water temperature might also have helped.

As with other responses to a specific field intensity, the orientation of fish in an electric field is a critical factor in determining whether the field is strong enough to cause mortality. Collins et al. (1954) demonstrated this by a homogeneous-field experiment in which 7-cm fish were held either parallel or perpendicular to the lines of current at 6 V/cm. Those held parallel to the lines of current experienced 42 V along their bodies (fish length x voltage gradient) and suffered 77% mortality whereas fish held perpendicular to the field experienced only about 6 V across the body (about 1 cm in width) and all survived. Exploratory experiments revealed no differences in mortality when fish faced toward the anode or the cathode. Collins et al. (1954) concluded that the effective, mortality-producing factor in field intensity was the total voltage across the fish (head-to-tail voltage) rather than voltage gradient. However, they also showed that within the limited size range of fish used in their experiments (5-11 cm), the total voltage required to induce a certain level of mortality varied inversely with fish length such that there was no size-related difference with regard to voltage gradient along the lines of current. Whaley et al. (1978) tested the survival of bluegill and fantail darter (*Etheostoma flabellare*, 2.5-7.5 cm) held parallel to the lines of current in PDC fields and reported as much as 75 to 95% mortality. Recognizing that their test fish were always subjected to the maximum voltage differential available, they suggested that under natural conditions in a stream, the percentage of fish killed directly by electrofishing should be notably less because fish would be randomly located, primarily aligned with water current, and, therefore, subjected to varying head-to-tail voltages.

Various factors other than orientation were reported to compound the effect of field intensity on mortality. Nearly all researchers testing the factor found that mortality at a particular field intensity (above the threshold) increased with time of exposure (McMillan 1928; Groody et al. 1950; Collins et al. 1954; Pugh 1962; and Whaley et al. 1978). When voltage gradient was held constant, mortality increased with water temperature and conductivity (Collins et al. 1954) and, in PDC, with pulse frequency (Whaley et al. 1978).

Like severe stress, fatigue, and mortality, spinal and related injuries have long been attributed to tetanizing currents, especially in AC fields. However, recent studies clearly document that significant numbers of these injuries also occur in PDC and to a much lesser extent in DC. Based on anecdotal observations and circumstantial evidence, it appears that spinal injuries can occur anywhere within the effective portion of the field, and possibly outside the threshold for taxis (Sharber and Carothers 1988; Sharber and Carothers *in* Reynolds et al. 1988; Sharber pers. commun.; Sharber et al. unpubl. ms. 1991; Meyer and Miller 1991, unpubl. ms. 1991). Circumstantial evidence includes observations of brands on fish netted relatively far from the electrodes. Also, Lamarque (1990) noted that a single pulse, and sometimes a low voltage, can be sufficient to cause the violent contractions resulting in such injuries, but he did not elaborate.

If seizures causing spinal injuries occur at thresholds less than required for taxis, it is probable that the incidence of spinal injury among fish that escape the field might be at least as great as among those that are caught. It also means that measures to reduce the zone of tetany or overall field strength might not have much impact on the frequency of these injuries relative to the number of fish caught.

The relationship between field intensity and electrofishing-induced injuries, beyond some threshold level, is unclear. In controlled pond experiments, Spencer (1967) consistently found two to three times more spinal injuries in bluegill subjected to more intense AC fields—9 to 16% in 230-V, 3.1-A AC versus 3 to 7% in 115-V, 2.0-A AC. Similarly Roach (1992) observed greater incidence of vertebral injuries among adult northern pike he exposed to homogeneous fields of 30- and 60-Hz PDC at 400 V (50% duty cycle, 0.98 and 1.76 mean V/cm) than at 100 V (0.25 and 0.44 mean V/cm)—10 and 12% versus 5 and 8%, respectively. However, Hudy (1985) reported low percentages of spinal-injury (0.8-2.4%) and no significant differences with regard to voltage levels for hatchery rainbow and brook trout exposed to 350-V, 700-V, and 760-V AC (250-300 Hz, 250 W continuous). But Hudy's results might simply reflect the use of small, low-intensity fields in water of very low conductivity (Sharber *in* Sharber and Hudy 1986) and low temperatures. Even more confounding than Hudy's results is the report of no injury by McCrimmon and Bidgood (1965) for hatchery reared rainbow trout (11-27 cm TL) exposed two to four times for 3 to 10 s each in 60-Hz AC fields averaging 1.5 and 0.8 V/cm and 120-Hz half-sine PDC fields averaging 1.4 and 0.7 V/cm. In this case, water conductivities (475 to 550 µS/cm) and temperatures (11 to 13°C) were moderate and at least the higher voltage gradients were probably adequate to induce some tetany.

In field experiments in the Colorado River, Sharber et al. (unpubl. ms. 1989, unpubl. ms. 1991) compared the incidence of injuries in large rainbow trout for three types of anodes using 60-Hz, 4-ms, rectangular-wave PDC. Each anode represented a different field intensity and distribution in its proximity. Use of a 1-m ring with ten 20-cm droppers represented low field intensity near its perimeter and resulted in injuries to 45% of the large trout collected. Use of a 30-cm sphere represented a medium field intensity but also resulted in injuries to 45% of the fish. Use of a 1.2-m long by 1-cm diameter steel cable represented a high intensity field near its surface and resulted in injury to 65% of the fish. However, because fish appeared to be attracted to the lower end of the cable electrode, stunned further below the water surface than with other electrodes, and, therefore, more difficult to net, Sharber et al. (unpubl. ms. 1989) suspected that the higher incidence of trout injuries for the cable electrode might have been due to longer exposure times as much as the higher field intensity near the electrode's surface.

Voltage differentials across fish must exceed some minimum value (threshold) before muscular seizures and spinal injuries are likely to occur. It follows that orientation of fish when they first enter the field (or later) might be a significant factor, as it is for other responses and mortality. However, in preliminary laboratory experiments, Sharber (pers. commun.) found the situation for spinal injuries to be opposite that discussed above for mortality (Collins et al. 1954). Using 60-Hz, 4-ms, rectangular-wave PDC to produce a homogeneous field, he recorded injuries in over 30% of the trout when they were held perpendicular to the electric current (head-to-tail voltage least) but in only 3% of the trout when they were held parallel to the current (greatest heat-to-tail voltage). Reduction of pulse frequency to 15-Hz (5-ms) also reduced injuries to 3% for trout held perpendicular to the current. These results further suggest that high field intensities and head-to-tail voltage differentials might not be critical factors in electrofishing injuries, at least when using PDC. The results also correlate well with early observations by Haskell et al. (1954) that upon circuit closure, muscular bending of fish toward the anode was greatest when fish were oriented perpendicular to the current and almost nil when they were oriented parallel to the current. The matter deserves confirmation and further investigation. Evidence that spinal-related injuries are usually far fewer in DC than PDC suggests that some attributes(s) of PDC fields in addition to field intensity must be responsible.

Length of Exposure

Whaley et al. (1978) concluded that mortality increased with both duration of exposure and pulse rate, but that duration of exposure had the greater impact (at least for frequencies of 16 Hz or less). Based on tests of fantail darter (3-8 cm) and bluegill (9-17 cm) held parallel to the lines of current in a homogeneous PDC field at 4 V/cm (154 µS/cm, 10°C), they found that mortality was low to negligible at durations up to 15 s, but that both mortality and recovery time increased progressively with longer exposures. Mortality was greater than 35% for exposures of 120 s and greater than 50% for 180 s. The combination of 16 Hz and exposures of 120 and 180 s resulted in about 75% to 95% mortality. Referencing unpublished data by O. Maughan and C. Schreck, Whaley et al. (1978) noted that mortality also increased with exposure time for fathead minnow (*Pimephales promelas*) and bluegill subjected to 160 V for up to 270 s (neither form of current nor field intensity were given). In practice, 20 s is a long exposure; in rivers, most fish are probably subject to electrofishing fields for less than 10 to 15 s (Bestgen pers. commun.). As noted above under "Field Intensity", McMillan (1928) testing salmon, Groody et al. (1950) testing sardines, Collins et al. (1954) testing chinook salmon, and Pugh (1962) testing coho salmon (*Oncorhynchus kisutch*) also reported that mortality increased with duration of exposure. According to Collins et al. (1954), Groody et al. (1950) found this relationship especially true with a non-pulsating current. Collins et al. (1954) also reported that the effect of duration of exposure on mortality increased directly with size of fish and water temperature.

Although time of exposure to tetanizing currents is an important factor in mortality, Spencer (1967) found no relationship between duration of exposure and the incidence of spinal injury in bluegill exposed to AC and DC fields. He compared several exposure times from 1 to 120 s in both types of current and concluded that these injuries occur immediately at the beginning of exposure. No other reports on the effect of duration of exposure on spinal or related injuries were found. However, observations of a direct relationship between pulse frequency and injuries (discussed below) suggest that duration of exposure should probably be a factor in PDC (longer exposures would subject fish to more pulses).

Pulse Shape, Waveform

Vibert (1967b), in agreement with Halsband (1967), claimed that exponential (i.e., capacitor- or condenser-discharge) waveforms have the greatest physiological effect on fish and are therefore among the best waveforms for electrofishing. But according to his associate, Lamarque (1967a), use of exponential waveforms in electrofishing was based on the false assumption that best results are obtained with high voltage or tetanizing currents. Lamarque (1967a) observed that exponential waveforms can kill an eel in 30 s and concluded that with their steep initial slopes and short pulse durations they are the worst form of PDC. Lamarque (1967a, 1967b, 1990) further documented the adverse effects of exponential, as well as half-sine waveforms in tests conducted with an assortment of gear in a stream. In these tests, Lamarque exposed trout to various electrical fields for 20 s while they were held about 20 cm from and facing a 40 cm ring anode. He reported mortalities of 86 to 93% for 80-Hz exponential waveforms (33% and 50% duty-cycle) and 89% for a 90-Hz, 400-V half-sine waveform (rectified AC, probably full-wave since no duty cycle was reported). In contrast, Lamarque (1967a, 1967b, 1990) reported 50% mortality for a 5-Hz, 400-V, 33% duty-cycle rectangular waveform; 17% for a 400-V rippled DC (partially smoothed, rectified AC); and only 6% for 500-V (smooth?) DC. Testing fish in the same currents at 50 cm from the anode, Lamarque (1967a, 1967b, 1990) recorded mortalities only for the half-sine PDC waveform (27%). He suggested that the high mortalities of the exponential and sine-wave PDCs might be attributed to their high frequencies.

Sharber and Carothers (1988, 1990) compared the injurious effects of three PDC waveforms on rainbow trout (30-56 cm TL) electrofished in the

Colorado River below Lake Powell. They reported that the quarter-sine waveform injured significantly more fish, 67% of 55 fish, than either the exponential or rectangular waveforms, 44% of 99 fish and 44% of 55 fish, respectively. Both the quarter-sine and rectangular waveforms were 260 peak volts, 60 Hz, and 25% duty cycle (pulse width of about 4 ms). Quarter-sine pulses also damaged significantly more vertebrae per fish (mean of 9.5) than did exponential pulses (mean of 6.6). The number of vertebrae damaged by rectangular pulses (mean of 8.2) was not statistically different from either of the others. Spinal injuries were not found in 12 non-electrofished trout of similar size from a hatchery. Immediate mortalities, if they occurred, were not reported.

Although the test conditions and adverse effects are not comparable, it is interesting to note that Lamarque's (1967a, 1967b,1990) 50% mortality for a rectangular waveform (5 Hz) is similar to Sharber and Carothers' (1988, 1990) 44% incidence of spinal injuries for the same waveform (but at 60 Hz). In contrast, Lamarque (1967a, 1967b, 1990) reported much higher mortality for exponential waveforms (>85%; 80 Hz) and concluded that they are among the most lethal PDCs, whereas Sharber and Carothers (1988, 1990) found their exponential waveform (60 Hz) to be no more injurious than the rectangular waveform.

Fredenberg (1992) compared electrofishing injuries for rainbow and brown trout using 60-Hz rectangular, half-sine half-rectified, and half-sine fully rectified PDC waveforms. He reported injuries for 78 to 98%, 65 to 90%, and 62 to 73% of the fish, respectively, depending on drainage or species. He also reported injuries for 31 to 54% of the fish using Coffelt's *CPS* pulse train (15-Hz packets or bursts of three 240-Hz rectangular pulses) and 44 to 64% using a hybrid DC-PDC waveform (top half of 60-Hz half-sine pulses above a half voltage DC baseline). These figures are based on the combined results for both necropsy (including minor hemorrhages likely to have been discounted or overlooked by others—Fredenberg pers. commun.) and X rays and do not take into account substantial differences in the severity of the injuries. Not only were fewer fish injured with the *CPS* current, but those injuries were usually much less severe than with other PDC waveforms (Fredenberg pers. commun.).

Pulse Frequency, Pulse Trains

Pulse frequencies in PDCs appear to be a significant factor in both mortality and spinal-related injuries. Lamarque (1967a) suggested that the high mortalities caused by exponential and half-sine waveform PDCs in his experiments might be attributed to their high frequencies, 80 and 90 Hz, respectively. But even for his 5-Hz rectangular-wave PDC, he reported 50% mortality. With regard to injuries in PDCs, Lamarque (1990) suggested that extent of injury depends mainly on pulse frequency and pulse duration. He concluded that "The worst currents are those with a pulse duration of 2-5 ms at 5-200 Hz." Yet these are precisely the PDC ranges most used in recent decades, including currents designed to reduce the occurrence of spinal injuries.

Both Collins et al. (1954) and Whaley et al. (1978) examined the effects of frequencies below 17 Hz. Collins et al. (1954) reported that mortality among YOY chinook salmon exposed for 30 s to experimental homogeneous fields of rectangular-wave PDC increased with pulse frequency from none for 5-cm fish at 3 Hz to a maximum of 75% for 11-cm fish at 15 Hz (4 V/cm, 48 µS/cm, 20-ms pulses). The effect of pulse frequency was compounded by increased length of fish and duration of exposure. Whaley et al. (1978) also found that mortality increased with pulse rate and was notably higher for 16 Hz than 8.8 or 1.6 Hz at exposures over 30 s. They concluded: "Our data showed relatively high mortality of fantail darters and bluegills in the pulse frequency defined as giving good electrotactic response." Collins et al. (1954) also observed that pulse duration, and therefore the total energy applied per unit time, does not appear to influence the incidence of mortality. Accordingly, they concluded that "change in potential" and the rate at which it occurs (i.e., pulse frequency, switching current on and off) significantly affect the extent of electrofishing mortality.

As noted earlier, Northrop (1962, 1967) found that rectangular-wave PDC was most effective at inducing taxis in 20- to 25-cm brown trout when run at 33 Hz with a 67% duty cycle (20-ms pulse widths). But at 100 Hz, 50% duty cycle (5-ms pulse width), he found fish were narcotized (tetanized?) at once, and showed no significant electrotaxic behavior. Examination of the latter trout revealed bloody vents. He attributed this internal bleeding to violent uncoordinated muscle spasms caused by the high pulse rate. No such hemorrhagic conditions were noted at the lower pulse rate. Still, Northrop (1962, 1967) reported that regardless of pulse rate, all fish recovered within a few minutes to swim and react normally to external stimuli.

McMichael et al. (1991) and McMichael and Olson (unpubl. ms. 1991) reported higher percentages of spinal injury among rainbow trout exposed to fields with higher pulse frequencies. They exposed 23- to 25-cm FL, hatchery-reared fish to 300-V DC (no pulses), 400-V DC, 300-V PDC at 30 Hz, and 300-V PDC at 90 Hz using a backpack electrofisher (the PDCs had a rectangular waveform and 12.5% duty cycle). The fish were then processed (anesthetized, measured, weighed, scale samples removed, and tagged) and monitored for 7 d, recaptured with the same currents, and 114 necropsied for vertebral damage or hemorrhaging. There were no immediate mortalities and only one fish died during the monitoring period. Injuries occurred in 4%, 17%, 35%, and 53% of the fish, respectively.

Unpublished research on the effect of PDC frequency and patterns by Sharber (pers. commun.) and Sharber et al. (unpubl. ms. 1989, unpubl. ms. 1991) also supports a direct relationship between pulse frequency and spinal injuries for pulse frequencies of 15 Hz or greater. In field experiments with spherical electrodes, Sharber compared injuries for rectangular-wave PDC at 15 Hz (5-ms pulse duration), 30 Hz (4-ms), 60 Hz (4-ms), and 512 Hz (0.2-ms). Respective incidence of injury were 3%, 24%, 44%, and 61%. A laboratory test of a 15-Hz current producing a homogeneous field of 0.5 V/cm also resulted in injury to 3% of the fish (Sharber pers. commun.). As noted above under "Type of Current", unpublished field trials with 15-Hz PDC reported by Fredenberg (pers. commun.) resulted in total injuries (including minor hemorrhages) to 10% of the white or longnose suckers, 20 % of the mountain whitefish, and 42% of the rainbow trout collected and examined by necropsy. However, obvious injuries to the spine or vertebrae themselves were much lower for the suckers and whitefish (only 2%), and about half (20%) for rainbow trout. Roach (1992) also observed higher percentages of injury in northern pike (36-74 cm FL) that were exposed to higher frequencies of PDC in homogeneous fields. Based on X rays, he reported vertebral injuries in 5% of the fish for 30 Hz and 8% for 60 Hz at outputs of 100 V, 10% for 30 Hz and 12% for 60 Hz at 400 V, and 29% for 120 Hz at 300 to 600 V (mean-voltage gradient of 0.93 V/cm). Also, based on 27 necropsies for each frequency, he observed no spinal-related hemorrhages for pike exposed to 30 Hz at 50 to 300 V but 15% for 60 Hz at 50 to 300 V. However, injuries observed by Roach (1992) for northern pike were much less obvious and less serious than those usually observed in trout (Roach pers. commun.). Contrary to the preceding reports, Newman (1992, unpubl. ms. 1991) found no difference in the incidence of spinal-injuries between walleye subjected to 120 Hz and those subjected to 30 Hz but output voltage (mean or peak?) was lower at the higher frequency, 200 V versus 310 V at 30 Hz.

Coffelt's *CPS* current produces packets or trains of three very rapid (240-Hz) pulses 15 times per second. Using *CPS* in the Colorado River, Sharber (pers. commun.) and Sharber et al. (unpubl. ms. 1991) reported injuries in only 7% of the rainbow trout over 30 cm in length (n = about 70). By comparison all 60-Hz PDC waveforms tested by Sharber and Carothers (1988, 1990) in the Colorado River had resulted in injuries to 44 to 67% of the trout collected. As noted above, Sharber (pers. commun.) and Sharber et al. (unpubl. ms. 1989, unpubl. ms. 1991) reported only a 3% incidence of injuries for 15-Hz PDC but found that taxis at this frequency was unsatisfactory for effective electrofishing. For a similar power output, *CPS* was also less effective than 60-Hz currents, but by increasing voltage output for *CPS* by about 20%, Sharber et al. (unpubl. ms. 1991) obtained a comparable response level. They also reported that in hatchery experiments *CPS* resulted in 6% spinal injuries whereas a 60-Hz, 4-ms, rectangular-wave current produced 18% spinal injuries.

Meyer and Miller (1991, unpubl. ms. 1991) and Wyoming Game and Fish Department (1991) compared the incidence of trout injuries for *CPS* with 40-Hz, rectangular-wave PDC (20% duty cycle). They concluded that both currents produced good anodic taxis and relatively low percentages of spinal injuries, an average of 8% for the 40-Hz PDC and 13% for *CPS*. Output voltages were about 20 to 25% higher for *CPS* (460-470 V) than 40-Hz PDC (370-390 V) to maintain comparable sampling efficiency.

Fredenberg (1992) also compared electrofishing injuries among trout electrofished with *CPS* and other currents but recorded notably higher percentages of injuries for all currents than have been reported elsewhere (in part because, unlike most other reports, his figures were based on the combined results of both necropsy and X rays; also, his necropsy data included minor hemorrhages that may have been discounted or overlooked by others using necropsy—Fredenberg pers. commun.). *CPS* injuries ranged between 31 to 54% of the fish and were substantially higher than reported by Sharber (pers. commun.), Sharber et al. (unpubl. ms. 1991), or Meyer and Miller (1991, unpubl. ms. 1991) and Wyoming Game and Fish Department (1991). In comparison with other waveforms, Fredenberg (1992) reported injuries in 62 to 98% of the fish for 60-Hz PDC rectangular and half-sine waveforms, 44 to 64% for a hybrid DC-PDC waveform (top half of 60-Hz half-sine pulses above a half voltage DC baseline), and 7 to 30% for DC.

Fredenberg (pers. commun.), as noted above under "Type of Current", compared the incidence of injuries produced by *CPS* (400 V, 22.4 A) with 15-Hz PDC (200 V, 17.5 A) and DC (110 V, 5 A) for three species collected by boat electrofishing in the Missouri River (October 1990, 10°C, about 450 µS/cm, n= about 50 for each species-current combination). Both total injuries (including many fish with only minor hemorrhages) and fish with injuries to the spine only were lowest for *CPS* (2-6% for total injuries, 0-2% for spine only, versus 8-18% and 0-6%, respectively, for DC and 10-42% and 2-20% for 15-Hz PDC.

Perhaps, as suggested by Collins et al. (1954) for mortality, convulsions resulting in spinal injury occur predominately as the current or pulse is "switched on". This might explain why fewer spinal injuries occur at lower frequencies in PDC and perhaps why even in straight DC (no pulses) some spinal injury has been observed (DC momentarily acting like PDC when switched on and off—Lamarque 1990). Indeed, Haskell et al. (1954) documented that in sufficiently strong fields, fish responded to each circuit closure with a muscular seizure that resulted in a bending of the body towards the anode. Interestingly, and counter to the concept of greater head-to-tail voltages yielding stronger responses, Haskell et al. (1954) found that the more nearly perpendicular the fish was to the lines of current, the stronger the bending response. Fish in-line with the current exhibited little if any bending of the body. Perhaps the convulsions resulting in these bends occur on both sides of the body but are proportionally stronger on the side facing the anode and essentially equal when the fish is parallel to the current.

Pulse Duration

Collins et al. (1954) reported that under the conditions of their experiments, pulse duration was not a lethal factor and that there was no direct relation between mortality and total energy applied per unit time. In controlled experiments on juvenile chinook salmon (5-11 cm TL) with homogeneous fields of 8-Hz rectangular-wave PDC, they found that fish exposed to a pulse duration of 20 ms (16% duty cycle) had the same mortality as those exposed to a pulse duration of 80 ms (64% duty cycle). Lamarque (1990), on the other hand, suggested that pulse duration, as well as frequency, has a major effect on the extent of injury. He particularly noted that pulse durations of 2 to 5 ms characterized some of the worst PDCs.

Voltage Spikes

There is often a voltage "spike" phenomenon that occurs with some equipment at the leading and sometimes posterior edges of a pulse or as a continuous current is switched on and off (Novotny pers. commun.; Sharber pers. commun.; Fredenberg 1992). According to Jesien and Hocutt (1990), the size of these spikes increases as water conductivity increases. While the voltage of such spikes can be much higher than the designed peak voltage for the pulse, the spikes are usually considered too short in duration to have any significant effect (Sharber pers. commun.). However, the matter may deserve further consideration. If such spikes are found to affect the incidence of spinal injury, it should be possible to electronically filter them out of the applied current (Novotny pers. commun.).

Species

Evidence to date suggests that trout, char, and probably salmon (subfamily Salmoninae) are more susceptible to electrofishing spinal injuries than most other species (Table 3; occurrences reported as high as 98% for trout—Fredenberg 1992). However, these salmonids, particularly rainbow, cutthroat, brown, and brook trout, are also the most frequently targeted species in electrofishing investigations. Only a few controlled laboratory or hatchery experiments compared the susceptibility of various species to spinal injuries. The Salmoninae also appear to be more sensitive to electrofishing mortality, but, again, available data for other species are few and not very comparable. In field experiments, specific frequencies of injuries and mortalities reported for various species are highly variable, and differences may not be easily related to type of current, its attributes, intensity of the field, or water conductivity and temperature. For example, in most recent studies, incidence of spinal injuries in rainbow trout were very high, but McCrimmon and Bidgood (1965) reported no skeletal damage attributable to either AC or PDC fields among 80 hatchery rainbow trout (11-26 cm TL) that were experimentally exposed in the laboratory or among 291 wild rainbow trout (6-59 cm TL) that were electrofished in Ontario streams tributary to the Great Lakes. All fish were X rayed (the hatchery fish before and after exposure), and some were dissected.

Among the Salmoninae, relative susceptibility to injury or mortality appears highly variable. Fredenberg (1992) found rainbow trout, and probably cutthroat trout, more susceptible to spinal and related injuries than brown trout. Data reported by Meyer and Miller (1991, unpubl. ms. 1991) and Wyoming Game and Fish Department (1991) suggested the same for fish in stream sections electrofished four times in succession with 40-Hz rectangular-wave PDC but the reverse for stream sections electrofished only once. However, in neither case were differences between species in Meyer and Miller's reports statistically significant (Meyer pers. commun.). The incidence of injuries reported by Meyer and Miller were similar for rainbow and brown trout when stream sections were fished only once with Coffelt's *CPS* current. Although mortalities and injuries were very low among trout electrofished with AC, Hudy (1985) reported significantly greater mortality among rainbow trout but greater numbers of fish with abnormalities, including spinal injuries, among surviving brook trout. Pratt (1955) compared mortality among hatchery rainbow, brook, and brown trout exposed to AC or DC fields. In both AC and DC, brown trout were most susceptible.

Very few species other than Salmoninae have been X rayed or examined by necropsy for detection of internal injuries caused by electrofishing. Spencer (1967) reported substantial occurrences of injury for channel catfish (at least 60% of 10) and bluegill (up to 16%) but almost no spinal injuries for largemouth bass. Roach (1992) reported injuries in 5 to 29% of the northern pike he exposed to homogeneous PDC fields (30 to 120 Hz). Holmes et al. (1990) documented 12.5% spinal injury for northern pike, none to 18% (but less severe) injury for Arctic grayling (*Thymallus arcticus*), and no injury for humpback whitefish (*Coregonus pidschian*) and least cisco (*Coregonus sardinella*). Fredenberg (1992) reported only one minor injury for Arctic grayling and no injuries among small numbers of sauger (*Stizostedion canadense*) and shovelnose sturgeon (*Scaphirhynchus platorynchus*). In contrast to Fredenberg's (1992) observations for sauger, Newman (1992, unpubl. ms. 1991) reported up to 31% injury for walleye (sauger's close relative). And, according to Pfeifer (pers. commun.), paddlefish (*Polyodon spathula*), apparently unlike shovelnose sturgeon, are highly susceptible to spinal-type injuries despite lack of a vertebral column. Pfeifer (pers. commun.) reported high mortalities among paddlefish electrofished with PDC in the Yellowstone and Missouri Rivers. Necropsy of these fish revealed that their notochords were badly ruptured. Several species of fish, including carp, suckers (Catostomidae), walleye, northern pike, and bass (Centrarchidae) were dissected for contaminants analysis by Krueger (pers. commun.), but he only recalled seeing substantial numbers of spinal injuries among trout. Similarly, in a field investigation intended to compare susceptibility to electrofishing injuries, Fredenberg (pers. commun.) found 2% to 20% injury to the spine for rainbow trout, depending on whether DC, 15-Hz PDC, or Coffelt's *CPS* were used, but only 0 to 2% for either mountain whitefish or suckers (white and longnose). However, when specimens with only hemorrhages along the spine or associated musculature (all minor) are included in the figures, the percentages of injured fish increased to 6% to 42% for rainbow trout, 2% to 29% for mountain whitefish, and 4% to 18% for the suckers. Clady (1970 according to Schneider 1992) reported some injury to smallmouth bass (*Micropterus dolomieui*) and white sucker with 560-volt AC gear, but Schneider (1992) did not specify whether these were spinal or other injuries. Whaley et al. (1978) reported as much as 75-95% mortality for both bluegill and fantail darter exposed for up to 3 min to PDC in laboratory experiments. Sculpins (Cottidae), according to Gowan (pers. commun.), are highly susceptible to extended tetany with flared opercules and subsequent mortality when captured in shallow riffles with outputs of 300 V or greater. Eloranta (1990) found burbot to be the species most sensitive to DC electrofishing mortality in the littoral zone of a Finnish lake. He reported that mortality for burbot was usually less than 25% but occasionally up to 50% when temperatures were high, whereas for other species, mortality was usually under 11%.

Among teleosts in North America, catfishes (order Siluriformes, mostly Ictaluridae) may be unique in their sensitivity and reaction to electric fields (Morris and Novak 1968; Corcoran 1979). Their lateral-line-canal sensory systems include electroreceptors (Peters and Buwalda 1972; Kramer 1990). This may account for their ease of capture using extremely simple and low voltage devices, some of which are legally banned in certain states (McSwain 1988). With the exception of Spencer's (1967) observations of high incidence of spinal injuries, noted above, adverse effects on catfish have not been studied and any relationship to the presence of special electroreceptors is unknown.

The Chondrostei, sturgeon and paddlefish, also have electroreceptors. Whether these fish are also more sensitive to electric fields has not been reported. Perhaps the high mortality and incidence of spinal (notochordal) injury reported for paddlefish (Pfeifer pers. commun.) are related to the presence of these organs.

Size

The general consensus, both by researchers experienced in electrofishing and in general texts on electrofishing, is that large fish are easier to electrofish than small fish. The relationship is supported by at least some studies comparing the size distribution of fish collected by electrofishing with the known size distribution of populations or comparable data collected by other techniques (e.g., McFadden 1961). Maxfield et al. (1971) subjected both YOY (about 5 cm TL) and yearling (about 19 cm TL) rainbow trout to 30 s of homogeneous, low-frequency PDC (1 peak V/cm at 8 Hz and 0.75 V/cm at 5 Hz, respectively) but observed narcosis only among the yearlings. Taylor et al. (1957) investigated the relationship between DC response thresholds and fish length by subjecting nearly 300 4- to 34-cm (standard length?) rainbow trout to homogeneous fields of 0.10 to 0.54 V/cm for up to 6 s. They recorded four levels of responses from inhibited motion or minor signs of distress to narcosis or tetany and reported decreasing response thresholds as size increased to 25 cm. But the relationship between response thresholds and size was not clear for the 10 fish they tested between 25 and 34 cm. Lamarque (1990) noted that the threshold for nerve response deceases with nerve length only for nerves shorter than about 4 cm and that the threshold remains constant for nerves of greater length. Accordingly, he concluded that except for small fish, this size-response relationship might be due to factors other than the effect of the electric field itself. Emery (1984) suggested that the relationship is based on total surface area of the fish rather than its length or weight.

With regard to mortality, the effect of field intensity appears to be independent of fish size. This was demonstrated by Collins et al. (1954) in experiments with juvenile chinook salmon (5-11 cm TL) in homogeneous fields of rectangular-wave PDC. Unlike the effect of field intensity itself, Collins et al. (1954) did conclude that the effects of duration of exposure and water temperature on mortality in an electric field of fixed intensity are dependent on fish size. Whaley et al. (1978) tested the effects of field intensity on bluegill and fantail darter in groups according to size and, like Collins et al. (1954), observed no significant size-related differences in mortality.

Interestingly, the lack of size dependency in the effect of field intensity on mortality led Collins et al. (1954) to conclude that since head-to-tail voltage at fixed field intensity with fish oriented parallel to the lines of current varies directly with the length of the fish (voltage gradient x fish length), there is a direct relationship between fish size and the total voltage (head-to-tail voltage differential) required to kill the fish. For example, according to Collins et al. (1954), approximately 60 V head to tail would be required in 48-µS/cm water to kill 50% of exposed salmon measuring 5 cm, whereas 140 V would be required for salmon measuring 11 cm. Similarly, in Whaley et al.'s (1978) experiments, the field intensities required to kill fantail darters and bluegills resulted in calculated head-to-tail voltages varying from 10 to 30 V and 36 to 68 V, respectively, depending on the length of the fish. Whether head-to-tail voltage is just an artificial mathematical relationship or a real factor in the effects of an electric field on fish is uncertain.

With regard to spinal injuries, the importance of fish size is also questionable. McMichael et al. (1991) and McMichael and Olson (unpubl. ms. 1991) reported a significant positive correlation between fish length and occurrence of injuries for rainbow trout between 14 and 48 cm FL. Similarly, Hollander and Carline (1992) reported that the incidence of injury among electrofished brook trout, 9 to 24 cm TL, also increased with size (from 14% for fish <13 cm to 42% for fish >18 cm). Among northern pike 36 to 74 cm FL that were subjected to similar electric fields, Roach (1992) found that those experiencing spinal injuries were significantly larger (57 cm) than those that were not injured (51 cm). However, in extensive surveys of spinal injuries among salmonids, neither Meyer and Miller (1991, unpubl. ms. 1991; also Meyer pers. commun.) nor Fredenberg (1992) found an overall relationship between the percentage of injured fish and size. Newman (unpubl. ms. 1991) noted that size might be a factor for walleye but his sample size (30 specimens, 18-48 cm) was too small and variable to be conclusive.

Condition

Some authors have suggested that spawning fish, particularly salmon, may be especially susceptible to spinal injuries, probably due to decalcification (Stewart 1967 as cited by Lamarque 1990). Fish whose diets are deficient in magnesium and calcium may also be more susceptible (Lamarque 1990).

Long-Term Survival and Growth

In a study to determine the effects of DC electrofishing (600 V, 200 W continuous) on mottled sculpin (3-9 cm standard length, SL), Barrett and Grossman (1988) monitored specimens collected by electrofishing and kick-seining for a month and reported no significant differences in delayed mortality (0-11% for electrofishing, 0-15% for kick-seine). Fish were collected in late winter from a stream near Otto, North Carolina, with water temperatures of 5 to 8°C and conductivity between 10 and 15 µS/cm. Although sample sizes were too small for statistical purposes, Barrett and Grossman (1988) also reported little or no mortality for largescale stoneroller (*Campostoma oligolepis*), rosyside dace (*Clinostomus funduloides*), warpaint shiner (*Luxilus coccogenis*), Tennessee shiner (*Notropis leuciodus*), longnose dace (*Rhinichthys cataractae*), creek chub (*Semotilus atromaculatus*), and northern hog sucker (*Hypentelium nigricans*).

Gatz et al. (1986) noted that although prior investigations failed to reveal any adverse effects on growth subsequent to single electrofishing events (Halsband 1967; Maxfield et al. 1971; Ellis 1974; Kynard and Lonsdale 1975), a variety of short-term physiological effects have been identified (Horak and Klein 1967; Schreck et al. 1976; Bouck et al. 1978; Burns and Lantz 1978). They suggested that repetition of these effects through repeated electrofishing as in multiple-capture studies might measurably affect subsequent growth. In a field study carried out for 1 year in very low-conductivity streams in Tennessee and North Carolina (5-10 µS/cm, salt blocks were necessary to raise conductivity), Gatz et al. (1986) monitored the individual growth of rainbow and brown trout of various ages that were repeatedly electrofished with 600-V, 120-Hz PDC twice within a 1 to 3 d period at intervals of 1.5 to 7 months. They reported that significant numbers of fish lost weight, both short-term (1-3 d, 81% lost an average of 5% of their body weight) and long-term (87% for fish electrofished within 3-month intervals, 56% for fish with electrofishing intervals greater than 3 months). The number of fish suffering long-term weight loss was greater among fish electrofished four or more times and among fish of smaller size (age 1 and 2). They concluded that "studies should be designed to avoid repeated electroshocking, especially at intervals of less than 3 months." They also suggested that "growth studies in which more than a small fraction (e.g., >20%) of the total population is repeatedly electroshocked at short (<3-month) intervals are likely to underestimate growth rates." Although no external signs of injury were noted, Gatz et al. (1986) mentioned tissue damage, which might require up to 3 months for complete recovery, as a possible explanation. Fish were not examined by X rays or necropsy to confirm this suspicion.

Gatz and Adams (1987) investigated the effects of repeated PDC electrofishing (400 V, 120 Hz) on the growth of hybrid sunfish (bluegill x green sunfish). They found growth of fish exposed to electric fields once a week for 3 months in the laboratory to be about 37% less than unshocked controls and 29% less than fish exposed once or every 2 or 4 weeks. Differences among unshocked controls and all treatments with less than weekly exposures were not statistically significant. Gatz and Adams (1987) concluded that time intervals between repeated exposures to electrofishing should be maximized to limit impacts on growth.

In a subdivided, outdoor, artificial stream, Barrett and Grossman (1988) conducted an experiment in late summer to determine the effects of weekly electrofishing on mottled sculpin over a 4-wk period. Both control fish (initially collected by kick-seine) and treatment fish were handled after each DC electrofishing event. Water temperatures were 12 to 14°C and conductivity was probably as low as in the experiment summarized above. Results were similar to the above experiment in that there were no significant differences in mortality between the treatment and control fish, although both experienced progressively higher mortality as the experiment proceeded (about 45-50% for electrofished and 35-60% for controls). Barrett and Grossman concluded that handling stress had a greater impact on delayed mortality than (DC) electrofishing, at least for mottled sculpin in low-conductivity streams.

Eloranta (1990) also experimented with the effects of repeated exposure to an electric field. He exposed burbot, ruffe (*Gymnocephalus cernua*), and bullhead (*Cottus gobio*) to 20 s of 550-V DC about 15 to 20 cm from the anode on each of 10 consecutive days. The fish ranged in size from 3 to 30 cm. During those 10 d he observed no differences in mortality between the experimental groups and controls and concluded that delayed effects were minimal.

Schneider (1992) stated that although AC electrofishing is an important technique, he had not found quantitative information about its effects on the survival and growth of warmwater and coolwater fish under typical field conditions. Accordingly, he monitored fish for immediate or delayed mortality and analyzed tagged-fish data to assess electrofishing effects on growth. This work was done in conjunction with mark-recapture studies in five Michigan lakes and ponds. As noted above under "Type of Current", he concluded that 3-phase AC electrofishing did not measurably increase the short-term mortality (1-33 d) of several species of warmwater and coolwater fishes. To compare longer-term survival and growth, he analyzed tag data for largemouth bass and walleye initially captured by electrofishing, trap netting, or angling. The results indicated no long-term effect on survival or growth by any of the three capture methods. With regard to electrofishing, Schneider (1992) noted that these results supported the conclusions of PDC studies by Gatz et al. (1986) and Gatz and Adams (1987) wherein growth was unaffected except when fish were electrofished repeatedly. Halsband (1967) stated that for carp it has been established that even long treatments with different types of current did not affect the fish's general condition or growth.

In another truly long-term study of growth and survival, Maxfield et al. (1971) documented the effects of low frequency PDC on the survival and growth of rainbow trout exposed as YOY and yearling juveniles. Several lots of fin-clipped YOY were exposed for 30 s in a homogeneous field of 8-Hz, 40-ms pulses at 1 peak V/cm (water 11-13°C, 143-172 µS/cm). Fin-clipped yearlings were similarly exposed but in a field of 5-Hz, 60-ms pulses at 0.75 V/cm (water 9-11°C, 114-132 µS/cm). The authors observed that during exposure 4% to 84% of the yearlings were narcotized but that all revived immediately. None of the YOY were narcotized by the field. All fish were alive 2 days after treatment. The fish were held with untreated controls of the same age group until maturity (held 2 years for yearlings, 3 years for YOY) and periodically monitored for mortality and growth. Cumulative mortalities for that period were 7.1% for those exposed as yearlings versus 10.4 % for controls and 9.9% for those exposed as YOY versus 16% for controls. Average lengths and weights near spawning time were 39 cm and 721 g for those exposed as yearlings versus 41 cm and 833 g for controls and 43 cm 861 g for those exposed as YOY versus 42 cm and 820 g for controls. Maxfield et al. (1971) concluded that exposure of YOY or yearling rainbow trout to PDC (low frequency) had no consistent effect on subsequent growth or survival.

Hudy (1985) reported less than 1% delayed mortality and less than 2% sustained abnormal behavior or externally obvious injury among 2,250 hatchery rainbow and brook trout monitored for 15 d after they were experimentally electrofished with AC (350-760 V, 250-300 Hz). Sharber (*in* Sharber and Hudy 1986) suggested that the low incidence of mortality and injury was probably due to the relatively small, low-intensity electric fields produced in very-low conductivity water (10 µS/cm). Low water temperature might also have been partially responsible. Only seven fish died during or immediately after exposure. Based on X rays, 21% of the 28 mortalities, 75% of the 36 abnormal survivors, and 1% of 96 normal survivors had vertebral fractures or dislocations attributed to the electrofishing event. No similar injuries were observed among control fish that were X rayed. Accordingly, less than 3% (approximately 55) of 2,250 electrofished specimens were estimated to have suffered vertebral fractures or dislocations, and of these, nearly 90% survived. However, over half (55%) of the injured survivors exhibited abnormal swimming behavior or external signs of injury; the remaining injured but normal-appearing fish could not be distinguished from uninjured fish without X rays or dissection.

Observations by other researchers also suggest that many fish survive spinal injuries. Spencer (1967) electrofished 10 channel catfish with 230-V AC and left them in the pond. Three were removed and dissected after the first day; each had fractured or dislocated vertebrae with associated blood clots. Three more were sacrificed and necropsied after 45 d; each had crooked or curved backs which did not appear to affect swimming. Internally, the damaged or misaligned vertebrae were obvious, healed, and stiff. Similarly, Fredenberg (1992) commonly observed old, healed spinal injuries in X rays of trout from some Montana samples. McMichael et al. (1991) and McMichael and Olson (unpubl. ms. 1991) reported only one death among over 100 hatchery rainbow trout exposed to electrofishing fields and held for 7 d prior to necropsy; some of these treatments experienced up to 53% incidence of spinal injuries.

Long-term effects of spinal-related injuries on behavior, growth, and survival could be serious management concerns for some species. Because of problems in objectively assessing the degree and impact of injury on a fishery, Holmes et al. (1990) recommended assessing the effects of electrofishing at the population level by testing for differential survival and growth over time between fish with electrically induced spinal injuries and control groups. Experiments of this nature were recently conducted on northern pike (Roach 1992) and rainbow trout (Taube 1992). Roach (1992) reported that after 10 to 11 months, there were no significant differences in growth or mortality between northern pike with spinal injuries and controls. The thesis by Taube (1992) was not received in time for this review. However, according to Reynolds et al. (1992), 45% of the hatchery-held rainbow trout exposed to electric fields died within seven months, and most mortality occurred in the first month.

Similar long-term studies are underway or planned elsewhere. L. Zeigenfuss, under the direction of E. P. Bergersen (Colorado Cooperative Fish and Wildlife Research Unit, Colorado State University), is conducting a study of long-term survival and growth among intentionally injured hatchery rainbow trout that have been released in a lake. S. Dalbey, under the direction of T. E. McMahon (Montana State University), will be comparing survival and growth of three separate lots of wild rainbow trout collected from the Gallatin River with DC, 60-Hz PDC, and Coffelt's *CPS* (Fredenberg pers. commun.). The only project of this type planned for endangered species in the Colorado River Basin was included in a proposal submitted to the upper basin's Recovery Implementation Program in spring 1992 by F. K. Pfeifer (Colorado River Fishery Project, U.S. Fish and Wildlife Service, Grand Junction, Colorado). The proposed investigation would include monitoring endangered species growth and survival in ponds after spinal injuries were electrically induced. The proposal also included documentation of the incidence of electrofishing injuries among endangered and related species collected in the Gunnison and Colorado Rivers of western Colorado and southeastern Utah.

Effects on Reproduction, Gametes, and Offspring

Spawning fish often aggregate in accessible localities and are sometimes considered more vulnerable to electrofishing than other life stages (Stewart 1967 as cited by Lamarque 1990; Kolz and Reynolds 1990b). For these reasons, studies employing electrofishing sometimes target the spawning season. Most of our knowledge of effects of electric fields on fish reproduction, gametes, and subsequent offspring is based on collection of brood stock, hatchery operations, and artificially fertilized eggs. The effects of electrofishing on the natural reproductive behavior of fish exposed while in ripe or near-ripe condition are unknown.

Halsband (1967) reported that gonads were unharmed by electrofishing, and Halsband and Halsband (1975, 1984) explicitly stated that "Harmful genetic effects—or harmful effects to the progeny—are also not produced." According to Vibert (1967b), "McGrath reported that . . . no ill effects have been recorded in hatcheries on the offspring of wild trout caught by electricity." Maxfield et al. (1971), who subjected YOY and yearling rainbow trout to 8-Hz and 5-Hz PDC, respectively, and documented the lack of effects on long-term survival and growth (see discussion on those aspects above), also reported that subsequent fecundity of those fish and mortality of their offspring through eyed-egg, hatching, and initial feeding stages was not consistently different from that of unexposed fish. Khakimullin and Parfenova (1981) reported no ill effects of pulsed 6-Hz, 40-ms AC (pulsed AC?) on Siberian sturgeon (*Acipenser baeri*) spawners or subsequent (pituitary-induced) gamete maturation and development of eggs and larvae. Similarly Valdez (pers. commun.) and Pfeifer (pers. commun.) reported no adverse effects of PDC electrofishing on ripe lake trout (*Salvelinus namaycush*) and walleye, respectively, or on the survival of their artificially fertilized eggs. However, other researchers have observed adverse impacts.

Marriott (1973) compared mortality of artificially fertilized pink salmon eggs from unshocked and electrocuted (110-V, 60-Hz AC) males and females. He found mortality through a late-eyed stage to be 12% higher for eggs from the electrocuted females. Two of the electrocuted females had severely ruptured internal organs and most of their eggs were loose and bathed in body fluids; this might have accounted for at least some subsequent egg mortality. Additional exposure of a batch of fertilized eggs from electrocuted adults to an electric field resulted in 27% greater mortality than for eggs which were never exposed to an electric field. Marriott recommended that electrofishing not be used to capture ripe females.

Newman and Stone (unpubl. ms. 1992) subjected ripe walleye to 120-Hz PDC (400 V, 3 A, quarter-sine waveform) and documented the viability of subsequently fertilized eggs. The fish were held in a net enclosure as an electrofishing boat made two slow passes about 0.7 m from the net. Mortalities for eggs artificially fertilized from the exposed fish, 63% to 65%, were significantly higher than the overall average, 37%, for unshocked brood stock. The authors also noted that the hatchery manager for the Lac du Flambeau Tribal Hatchery, L. Waronowicz, who cooperated in their experiments, had severe viability problems with eggs from electrofished brown trout. He and other hatchery managers had observed broken eggs when stripping electrofished brown trout and suspected that the albumen from the eggs might clog the micropyles in many unfertilized eggs. The authors also noted that some researchers suspected that electrofishing ripe males might cause a loss of sperm motility.

Effects on Early-Life Stages

Electric fields are of no value in the collection of fish eggs and few researchers have applied electrofishing technology to the collection of fish larvae and early juveniles (Snyder 1983; Copp 1989). Accordingly, most of the concern over adverse effects on fish eggs and larvae is with regard to incidental exposure during electrofishing operations for larger fish. However, as noted by Lamarque (1990), information on the effects of electric fields on early-life stages of fish is sparse and limited primarily to salmonids.

Kolz and Reynolds (1990b) surmised that the sensitivity of embryos to electrofishing is similar to that of mechanical shock and Lamarque (1990) cautioned that, because of the sensitivity of embryos between fertilization and eyed stages, electrofishing over active spawning areas should be avoided. For brook trout and Atlantic salmon embryos, Godfrey (1957) found sensitivity to electric fields was low through the first few hours (water hardening; precleavage stages), then high until the embryos were eyed, and low again thereafter. Dwyer and Fredenberg (1991) and Dwyer et al. (unpubl. ms. 1992) compared the effects of mechanical and electrical shock on rainbow trout embryos and documented differences in sensitivity from 2 to 26 d after fertilization for embryos cultured at 10°C (at this temperature, most eggs eyed-up at day 18 and hatched at day 28). They found that sensitivity followed a nearly normal distribution for both types of shock with peaks at day 8. Mortalities during this most sensitive time (day 8) averaged 99% for embryos subjected to mechanical shock (eggs dropped 15 cm from one container to another), 58% for those exposed for 10 s to a homogeneous PDC electric field (250 Hz, 0.9-1.0 mean V/cm, about 3.4-3.8 peak V/cm), 30% for handled but unshocked embryos, and about 20% for unhandled controls.

Newman and Stone (unpubl. ms. 1992), in addition to the experiment discussed above, tested the viability of 24-h and 48-h walleye eggs that were exposed to an electrofishing field. The eggs were placed in nylon mesh bags which were laid on a lake bottom over typical walleye spawning substrate. They were exposed to a single pass of the electrofishing boat (PDC-120 Hz, 400 V, 3 A, quarter-sine waveform). Mortality for 24-h eggs exposed to the electrofishing field was 64% whereas unshocked controls experienced 45%. In tests with the 48-h embryos, mortality was 56% for exposed eggs and 53% for controls; although small, the difference between exposed and unexposed eggs was significant. Noting that the incubation period for walleye eggs is much shorter than for trout eggs and that peak sensitivity to mechanical shock occurs at about 24 h of age, the authors suggested that for walleye embryos, the 24th hour also approximates the peak period of sensitivity to electric fields (compared to the 8th day for rainbow trout discussed above).

Embryos may also be detrimentally irritated by electric fields near the end of the embryonic period. Luczynski and Kolman (1987) used AC to induce precocious hatching in powan (*Coregonus lavaretus*) embryos.

Godfrey (1957) found that for brook trout and Atlantic salmon exposed to DC, mortality increased with exposure time and field intensity. Dwyer and Fredenberg (1991), Dwyer and Erdahl (1992) and Dwyer et al. (unpubl. ms. 1992) arrived at the same conclusion based on their own experiments with 8-d cutthroat trout embryos exposed to PDC. Mortalities observed after exposure to 5, 10, or 20 s of Coffelt's *CPS* waveform in a homogeneous field were approximately 100% at about 6.7 peak V/cm, 85-100% at about 5.3 V/cm, 20-45% at about 3.8 V/cm, and less than 15% for both 2.4 V/cm and for unshocked controls.

Scheminzky (1922 according to Lamarque 1990) subjected (brown ?) trout eggs to long exposures in a DC field and reported movements of embryos and one incident of high mortality. Although exposures in Scheminzky's experiments were far longer than those likely in normal electrofishing operations (Lamarque 1990), perhaps they were not so different from conditions near some electric screens or barriers which might affect floating or pelagic eggs such as freshwater drum (*Aplodinotus grunniens*), emerald shiner (*Notropis atherinoides*), or striped bass (*Morone saxitilus*).

Based on a limited experiment with precleavage Atlantic salmon eggs buried under about 20 cm of gravel and exposed to DC for about 2 min., Godfrey (1957) concluded that eggs in gravel redds received some protection from shock (mortality 10% versus 81% for unburied eggs). In a similar experiment, Dwyer and Erdahl (1992) and Dwyer et al. (unpubl. ms. 1992) subjected 8-d (cutthroat ?) trout eggs buried in artificial redds to backpack electrofishing fields. Cumulative mortalities 10 d after exposure were 96% for the Coffelt *CPS* waveform at 550 or 700 peak V, 68% for 250-Hz or 500-Hz PDC at 340 or 380 (peak?) V, and 56% for unshocked controls. The high mortality for the controls and a portion of each shocked group was attributed to sedimentation in redds. As a result of this and other experiments noted above, Dwyer et al. (unpubl. ms. 1992) concluded that electrofishing in streams where trout have recently spawned can adversely affect egg survival.

Among the few researchers who have used electric fields to capture larvae, Maty et al. (1986) used them to capture Atlantic salmon larvae upon emergence from redds and Noble (1970) used an electric grid in front of a Miller high-speed sampler to successfully improve the catch of larger larvae and juveniles. Noble (1970) found the field had little effect on the catch rate of smaller larvae. However, because smaller fish larvae are much less likely to evade the sampler, catch rates might not be expected to differ even if the field was effective.

Perhaps the greatest proponent for electrofishing as a sampling method for larvae and small juveniles is G. H. Copp of France. Copp and associates (Copp 1989, 1990; Copp and Penaz 1988; Persat and Copp 1990) utilized the same portable PDC electrofishing gear that is used locally for larger fish but modified the size of the electrodes (e.g., reducing anode to 10-cm ring while increasing the size of the cathode) to sufficiently intensify the field around the anode to induce taxis or narcosis (or tetany) in fish as small 5 mm SL. This resulted in an effective field diameter of 30 cm or less for most larvae and small juveniles. For larger fish, it is generally recommended that both electrodes be as large as possible to reduce the zone of tetany and maximize the effective size of the field. However, Copp and his associates effectively used their very limited range to advantage by combining the method with a sampling strategy that consisted of numerous, small, randomly distributed, microhabitat samples (Point Abundance Sampling). With this approach, the anode, on a 2.5 m handle, was dipped into the water as the deadman switch on the handle was closed, the net and current were maintained there for a second or two, and then a fine mesh dip net was thrust under the anode to collect the fish. The advantage over simply using dip nets or hand seines was a relatively unbiased size range. The matter of electrofishing injuries and mortality with this sampling method and design would not have been a serious concern because sample size was usually very small and larval and small fish samples were fixed and preserved for subsequent processing. But this might not be the case in other early-life-stage sampling or monitoring programs.

The effects of electrofishing on early-life stages appear to vary with species and size. Godfrey (1957) observed that newly hatched Atlantic salmon (*Salmo salar*) exhibited increased swimming movement in response to a DC but not taxis. Maxfield et al. (1971) noted that 30 s exposures to homogeneous, low-frequency PDC fields of 1 peak V/cm failed to induce narcosis in 5-cm YOY rainbow trout whereas exposure to similar fields at only 0.75 V/cm were sufficient to induce narcosis in at least some 19-cm yearlings. Among adverse effects, Lamarque (1990) noted that mortality was common for larval pikeperch (*Stizostedion lucioperca*) but rare for trout larvae; also that salmon parr did not suffer unduly in fields that killed larger smolt. Lamarque (1990) suggested that electric fields that are dangerous to adults would likely also be dangerous to juveniles, but because fish larvae and early juveniles are extremely fragile, mortality due to handling and the stress of capture would likely be as great as that due to electrofishing fields. The occurrence and significance of physical electrofishing injuries to fish larvae and early juveniles has not been documented in literature reviewed for this report.

SUMMARY OF SURVEY RESPONSES

A questionnaire (Appendix II) to assess local observations and recommendations with respect to electrofishing was distributed directly or through endangered-species program leaders to fishery biologists with electrofishing experience in the Colorado River Basin and to fishery faculty and graduate students at Colorado State University. Eleven written responses were received—two from the lower basin, seven from the upper basin, and two from university graduate students without Colorado River Basin experience. Pertinent comments from telephone or personal discussions with two additional upper basin researchers were also considered in the following summary of responses.

Experience

The level of experience represented by survey respondents was very broad and extensive, both in and outside the Colorado River Basin. Most respondents had at least 6 years of electrofishing experience and served as crew leaders or supervisors; one had been electrofishing for over 20 years. At least four took the U.S. Fish and Wildlife Service Fisheries Academy course on electrofishing. One taught a course on electrofishing. At least two had been involved in the development or modification of electrofishing gear.

Most respondents have electrofished in a variety of habitats from large rivers (with flows up to about 840 m^3/s) to small streams and major reservoirs to small lakes and ponds. Most electrofishing was done during spring through fall, but a few respondents also had experience electrofishing during winter in icy conditions. Temperatures during electrofishing were usually between 10 and 20°C but sometimes as low as 0°C or over 30°C. Most electrofishing, especially in the Colorado River Basin, took place in water conductivities of 300 to 1500 µS/cm, but some respondents had experience with electrofishing in conductivities so low (down to 10 µS/cm) that salt blocks had to be used to artificially raise the conductivity level or so high (2,000-5,000 µS/cm) that the power supply would shut down. Turbidity ranged from clear to very turbid, often moderately to highly turbid in the Colorado River Basin. Most respondents had experience with both day and night electrofishing.

According to respondents, boat and raft electrofishing were typically used in Colorado River Basin studies and monitoring programs, but most respondents also had experience with wading systems (backpack, barge, or bank equipment). At least one had experience with fixed position electrical grids, electric seines and an electric life net. Most systems were commercial (Coffelt, Smith-Root, and Georator). The Coffelt *VVP-15* was mentioned most frequently. PDCs were the most frequently used currents, but a few noted that when the situation allowed (e.g., low to moderate conductivities), they preferred to use DC. PDC parameters were seldom reported, but two stated that they used frequencies of 30, 40, or 60 Hz. One respondent never bothered with pulse width and frequency controls since consensus seemed to be that they were not very important. When reported, voltages and currents for effective electrofishing, mostly in the Colorado River Basin, were reported as 200 to 350 V and 4 to 8 A, but some reported use of up to 12 A. One respondent noted that in very turbid waters, their system had to be "cranked up" as high as possible to stun the fish well enough to bring them to the surface (a procedure since modified due to concern for injury). Use of AC was reported by only one respondent—many years ago in stream wading situations. Electrode use was highly variable. Spheres were favored as anodes for boat and raft electrofishing, but dropper rings and single or multiple cables were also used. Metal boats, very long single or multiple cables, and spheres were typically used as cathodes. Some respondents changed electrode size or configuration according to the specific waters being sampled (e.g., smaller spheres for more conductive waters).

Observations of Adverse Effects on Fish

Some respondents noted that most electrofishing efforts were inadequately documented. Not only were notes on specific electrofishing gear, configuration, procedure, waveform, instrument settings, meter readings, and physical measurements frequently neglected, but in many cases, even electrofishing mortalities, injuries, and other adverse effects were not recorded. Most respondents had to rely on their memories for recollections of adverse effects. This matter has been rectified in some recent Colorado River Basin investigations (Valdez pers. commun.). But even with comprehensive records, a few respondents suggested that because of differing environmental conditions, equipment configurations (especially type, number, and size of electrodes), and control box settings, it would be very difficult to correlate the incidence of injuries with those factors. One critical set of information takes into account many of these variables but appears to have been overlooked in most Colorado River Basin investigations—actual measures of field intensities (voltage gradients) for determination of intensity distribution and field size. These data could be invaluable for comparing electrofishing results and adjusting power output and electrode size or configuration to maintain comparable fields within and between sites. In lieu of in-situ measures, field-intensity distribution can be approximated by calculation if water conductivity, the size and shape of the electrodes, and peak output voltage, amperage, or power is known. Except for one investigation in which fish were dissected for contaminant assessments (Krueger pers. commun.), no provision was made for assessment of spinal or other internal injuries caused by electrofishing. Most observations of injuries noted below and included in Table 3 were based solely on visible, external signs of injury (e.g., brands). Of course, until recently, few researchers suspected the occurrence of spinal injuries, and often, even brands were not considered serious.

Respondents reported that in the Colorado River Basin they electrofished most species present in the areas sampled but that they rarely (in some cases never) experienced mortalities or injuries directly attributable to electrofishing, except for occasional brands. Several respondents have electrofished a wide range of size groups, from less than 4 cm to over 90 cm TL. Among fishes that were injured or branded, salmonids were found to be most susceptible (Table 3). In one case where fish were filleted for contaminant analysis, many captured rainbow and brown trout were found to have broken spinal columns posterior to the dorsal fin, whereas such damage was not observed for other species (Krueger pers. commun.; Burdick pers. commun.). Nearly all the salmonids with damaged vertebrae also had externally obvious brands. Such brands were sometimes observed on over half of the trout collected. Brands or other injuries and deaths observed by respondents were frequently assumed to be caused by direct contact with anode(s), especially cable anodes. No obvious signs of injury were reported for channel catfish, but two respondents noted that the species was extremely susceptible to tetany and slow to recover from it.

Although obvious adverse effects of electrofishing appear to be rare among Colorado squawfish (*Ptychocheilus lucius*), humpback chub, and razorback sucker (*Xyrauchen texanus*), these fish are susceptible. Brands (probably resulting from spinal injuries) have been reported for all three species, and at least one mortality and one occurrence of bleeding gills were reported for Colorado squawfish (Table 3). As further evidence that the endangered species do not appear to be seriously affected by electrofishing, some respondents noted that many electrofished and tagged specimens have been recaptured, sometimes repeatedly over a period of several years, and display no obvious aftereffects. Also, many electrofished and radiotagged specimens were successfully tracked for extended periods of time. Valdez (pers. commun.) suggested that with regard to long-term effects, physiological stress and damage to the nervous system may have the greatest impact on these fish, but such effects would be very difficult to assess.

One comparison of particular interest to many biologists concerned about spinal injuries, is whether Coffelt's new *CPS* gear has an advantage over presently used favorites (e.g., Coffelt's *VVP-15* and Smith-Root's *GPP*) in reducing injuries while maintaining electrofishing efficiency. Contrary to better documented results elsewhere (Sharber et al. unpubl. ms. 1991; Meyer and Miller 1991, unpubl. ms. 1991; Wyoming Game and Fish Department 1991; Fredenberg 1992, pers. commun.), Trammell (pers. commun.) observed that there seemed to be proportionately more brands among rainbow trout and humpback chub collected with *CPS* in the Grand Canyon than with the *VVP-15* in the upper basin. However, Valdez (pers. commun.) noted that such comparisons are questionable without both units being used in the same waters at about same time.

With regard to experiences outside the Colorado River Basin, Respondents submitted several notable observations from outside the Colorado River Basin. Gowan (pers. commun.) noted that among salmonids, electrofished specimens seldom showed external signs of spinal injury upon initial capture, but spinal injuries were sometimes evidenced a year later in fish that had stopped growing posteriorly and began to look like footballs. He also noted that the only significant electrofishing mortality he had observed was among sculpins captured in shallow riffles with outputs of 300 V or greater. The gills of these fish flared (probably in a state of tetany) and the result was often death.

Pfeifer (pers. commun.) reported high mortalities among paddlefish electrofished with PDC in the Yellowstone and Missouri Rivers. Upon necropsy, the notochords of these fish were found to be completely ruptured. Obviously, spinal injuries are not restricted to fish with vertebrae. Pfeifer noted that the rivers electrofished were very turbid and suspected that many of the fish had made direct contact with cable anodes or were exposed to excessively high field intensities.

In Alaskan streams, Valdez (pers. commun.) reported a high incidence of brands among all sizes of dolly varden (*Salvelinus malma*), pink salmon, and threespine stickleback electrofished with AC.

However, many of these fish were recaptured a year or two later.

Two respondents used electrofishing to capture ripe fish for culture. Valdez (pers. commun.) reported taking a 9 kg female and several 0.9 to 2.2 kg male lake trout with no obvious detrimental effects on the subsequently released fish or their progeny. Egg survival was high. Pfeifer (pers. commun.) reported similar use of electrofishing to capture ripe walleye. He also observed no detrimental external effects on the brood fish or the percentage of eggs that hatched.

Many respondents suggested that handling of fish during and after netting probably has a greater effect on mortality and delayed recovery than the electric field itself. Overcrowding and old, poorly oxygenated, holding water was recognized as a serious problem.

Respondent Recommendations for Minimizing Adverse Effects

Approximately half the respondents suggested the following measures for minimizing adverse effects on fish:

- Use the lowest power output that still provides for effective electrofishing (sufficiently large range for taxis and narcosis). In the Upper Colorado River Basin, Tyus (pers. commun.) suggested that amperage should normally be no more than about 5 or 6 A and that if red shiner (*Cyprinella lutrensis*) are being stunned, the amperage is too high. Gowan (pers. commun.) recommended that fish be observed following capture to ensure that they recover equilibrium within 1 to 2 min; if not, power should be reduced. Kinsolving (pers. commun.) suggested that the critical measure with respect to fish injury is voltage gradient, not output voltage or amperage per se. A simple home-built meter could be constructed and used to quantify or monitor field strength across different waters and to locate hot spots in the field. Field strength should be closely monitored in highly conductive backwaters and flooded tributaries. Hawkins (pers. commun.) noted that in the spring, fish, such as Colorado squawfish, are often confined to these habitats where they are especially susceptible to electrofishing.
- Use the least damaging current available, DC whenever circumstances allow; don't use AC. However, the occurrence of brands and extended tetany when using *CPS* indicates that adverse effects are still a problem even for currents designed to be less harmful.
- Use spherical electrodes and vary the number and size of spheres according to water conductivity and desired field size and intensity. However, Valdez (pers. commun.) noted that while spherical electrodes are theoretically superior to cables, he had not observed a significant difference in catch rate or the incidence of brands. Also, spherical electrodes limit the depth from which fish are drawn; Valdez (pers. commun.) suggested that spherical anodes and cable cathodes appear to be the best combination. Tyus (pers. commun.) recommended that anode(s) be kept high in the water to draw fish to the surface where they can be easily netted.
- Minimize exposure to the field and specimen handling—rapidly net fish before they get too close to the anode, and quickly, but gently, place them in oxygenated holding water. Tyus (pers. commun.) suggested that the foot-switch should not be closed continuously and that it should be released as soon as fish are observed near the anode. He also warned against over-working specific sites to maximize the numbers of fish captured. Buntjer (pers. commun.) cautioned that netters should not allow fish to remain in the net too long or repeatedly dip fish back into an active electric field. Valdez (pers. commun.) noted that underwater lights improve netting efficiency.
- Change the holding water frequently to ensure adequate dissolved oxygen and avoid excessive temperatures on hot days; also process the fish frequently to reduce crowding.

Some respondents emphasized the need to use trained personnel to properly operate the equipment under changing conditions and the best netters to quickly spot and remove fish from the electrical field. Tyus (pers. commun.) also emphasized that electrofishing trips should be scheduled to take advantage of conditions for the most efficient capture of target species (e.g., spring when conductivity is relatively low and endangered species of fish are still in the shallower near-shore habitats). Electrofishing should not be attempted under turbid or windy conditions—the fish can't be easily seen. Valdez (pers. commun.) emphasized the need to adequately document electrofishing operations and observations of adverse effects. Those that have done so in the past have a valuable source of information. Analyses and summarizations of this information might be useful in resolving the question of electrofishing injury, at least in the specific situations documented.

CONCLUSIONS

Injuries, especially spinal injuries, may be an unavoidable consequence of Electrofishing. However, the frequency and severity of these injuries and their significance with respect to populations varies with species, biological and environmental conditions, electrofishing gear and procedures, and the perceptions and attitudes of persons using the technique. Based mostly on survey responses and personal communications, biologists participating in electrofishing operations generally reported little obvious injury or mortality. Even brands ("burn" marks) were seldom reported to occur in significant numbers, and then mostly for salmonids; however, these may have been overlooked as relatively minor and short-term effects rather than as indications of internal injuries. Still, as emphasized by Sharber and Carothers (1988), without analysis by X rays or necropsy, most spinal and related injuries, unless especially severe, probably go undetected. In studies where electrofished specimens have been examined by these techniques, the number of reported electrofishing injuries usually goes up dramatically, at least for certain species (e.g., Sharber and Carothers 1988, 1990; Holmes et al. 1990; McMichael et al. 1991; Meyer and Miller 1991; Fredenberg 1992; Hollander and Carline 1992; Newman 1992).

In the Upper Colorado River Basin, electrofishing is one of the principal collection techniques for studying endangered and other fishes. Here too, few electrofished specimens other than salmonids have been reported to be injured, but again, none were X rayed and few were sacrificed for necropsy. Brands have been reported for many species, including endangered fishes, but they appear to be an infrequent occurrence. Many Colorado squawfish and smaller numbers of humpback chub and razorback sucker have been electrofished, radiotagged, and subsequently monitored for extended periods of time (Wick et al. 1985, 1986; Tyus and McAda 1984; Tyus et al. 1987; Tyus and Karp 1990; Osmundson and Kaeding 1989; Valdez and Masslich 1989). Most survived and appeared to behave normally. A far greater number of endangered and other fish initially collected by electrofishing were tagged with dangler, anchor, coded wire, or "PIT" tags. Some of these fish have been recaptured one or more times by electrofishing or other means, sometimes several years later (J. Hawkins pers. commun.). If the fish that were recaptured had incurred electrofishing injuries, the injuries were not obvious (or not documented) and did not affect survival between captures. However, some recaptured fish grew very little in length or not at all between captures, even when recaptured a year or more after the initial or prior capture; a few recaptures measured even less than at their prior capture (Bestgen et al. 1987; J. Hawkins pers. commun.). Spinal injuries, including compressed vertebrae, or severe physiological stress might account for at least some of these poor or no growth observations. Electrofishing-induced injuries do not appear to be a serious problem for endangered cypriniform fishes in the Colorado River Basin using most present gear and techniques, but that conclusion must be confirmed with hard data. Every practical means should be immediately employed to minimize adverse impacts.

RESPONSE TO SPECIFIC QUESTIONS

Prior to this investigation, M. Yard (GCES Aquatic Coordination Team, Bureau of Reclamation, Flagstaff, Arizona) assessed the information needed by the National Park Service and assembled a list of specific questions to be addressed by this, and if need be, subsequent investigations. The questions (edited and reordered as necessary) and answers based on this review of literature and communications with biologists in and out of the Colorado River Basin are as follows:

1. Does electrofishing impact native species of fish as severely as rainbow trout?

Except for the Colorado River cutthroat trout (*Salmo clarki pleuriticus*) in the headwaters of the upper basin, we suspect native Colorado River Basin species are not as susceptible to electrofishing injury as rainbow trout, but the evidence is largely anecdotal and hard data are needed. Many Colorado squawfish, humpback chub, and razorback sucker have been captured by boat or raft electrofishing, some repeatedly in tagging studies. In over a decade of field research and monitoring studies, Colorado River Basin researchers have reported very few incidents of mortality or obvious external injuries due to electrofishing, including brands. Still, none of these fish were examined by X rays or necropsy for spinal injuries and none of these species have been subjected to controlled experiments to establish susceptibility to electrofishing injury. It is important to recognize that except for a higher incidence of brands, the same statements could have been said for trout collected in the Colorado River Basin prior to Sharber and Carothers' (1988) investigations.

2. Do we know the effects of electrofishing on all native fish species? If not, what fish would be most representative of humpback chub anatomically and physiologically?

No, we don't know the effects on all native fishes. Under appropriate circumstances (i.e., electrofishing where and when the fish are likely to be found, equipment and techniques suited to the habitat, sufficient electrical fields for the species and size of fish targeted, and limited avenues for escape), all freshwater fishes, native or otherwise, are probably susceptible to capture by electrofishing. Whether an electric field will elicit similar responses in all species is not known, but when responses are similar, the electrical thresholds probably vary somewhat with species and size. Under certain conditions, all species are probably susceptible to some electrofishing injury, but the nature and degree of those injuries will probably vary with species.

There are no published accounts of the specific responses or adverse effects of electrical fields on native species of the Colorado River Basin except for cutthroat trout and mottled sculpin. Mesa and Schreck (1989) studied the behavioral aftereffects of electrofishing on cutthroat trout and reported cover seeking and reduced feeding, activity, and sensitivity to environmental stimuli as the principal effects; 3 to 4 h were required for half the fish to return to normal behavior. Fredenberg (1992) reported that cutthroat trout had nearly the same high incidence of spinal injuries as rainbow trout (as high as 90-98% in West Fork Bitterroot River collections in Montana). Barrett and Grossman (1988) studied the effects of single and repeated electrofishing events on survival of mottled sculpin. Although mortality for single-event tests ranged from 0 to 12% and those series of weekly exposures ranged from 45 to 50%, the results were not significantly different from controls collected by kick-net. Barrett and Grossman concluded that mortalities were caused more by handling stress rather than by electrofishing. Published information on electrofishing effects on non-native Colorado River Basin fishes is listed by species in the appended bibliography (Appendix I). Personal communications with Colorado River Basin researchers (including responses to a survey) revealed at least some observations of electrofishing mortalities, brands, or other injuries for native species, including each of the endangered species (Table 3).

The roundtail chub (*Gila robusta*) is a very close relative of the humpback chub and the most similar non-endangered species in the Colorado River Basin. Although we know no more about its susceptibility to electrofishing injury than we do about humpback chub, it is a common and readily available species in upstream portions of the Upper Colorado River Basin and could therefore serve as a surrogate for humpback chub in controlled field and laboratory studies. However, for laboratory and rearing-pond experiments, a surrogate species might be unnecessary. Humpback chub, as well as bonytail (*Gila elegans*, the other closely related but endangered species in the chub complex), Colorado squawfish, and razorback sucker, are or have been reared by federal hatcheries and sufficient specimens might be available for experimental purposes. Since some researchers have suggested that hatchery stocks, at least for salmonids, tend to be less susceptible to electrofishing injuries than wild stocks, the results of experiments using hatchery stock should be interpreted accordingly. Upper Colorado River Basin researchers are also concerned about the potential for electrofishing injuries to Colorado squawfish and razorback sucker (as well as bonytail should populations be reestablished). The adverse effects of electrofishing will also have to be investigated for these species or appropriate surrogates.

The one Colorado River Basin fish for which electrofishing effects are best documented is the rainbow trout. If only gross similarity in shape is considered, smaller specimens could be considered somewhat similar to the chubs. However, among the fishes for which electrofishing injuries have been documented, rainbow trout and its close relatives appear to be much more susceptible to such injuries. And of course, concern resulting from extrapolation of known effects on larger rainbow trout to humpback chub and other endangered and native species is what brought about this investigation in the first place. Therefore, it might be instructive to replicate experiments conducted on humpback chub, or a closely related surrogate species, with similar-size rainbow trout and compare results. If rainbow trout is confirmed as the most susceptible species in the basin, measures to minimize injury to it should assure minimal injury for all other species.

3. What exists in the literature related to physiological responses and stress due to electrical stimulation?

Well over a hundred publications listed in the bibliography include information on these matters (Appendix 1, see index). All responses to electric fields, from reactive detection through tetany, are physiological. Even electrocution and the momentary but powerful convulsions believed to cause spinal and related injuries are physiological phenomena.

Exposure to tetanizing currents often leads to at least temporary respiratory failure and synaptic fatigue, but fish usually recover equilibrium and normal breathing within minutes after removal from the field. Excessive exposure to tetanizing currents can result in very long recovery periods or death.

Stress disrupts normal behavior and osmoregulatory functions. All capture methods and handling are stressful. That caused by electrofishing is similar to stress caused by hypoxia and intensive muscular activity. Electrofishing stress and fatigue are physiological responses that usually require only a short time for recovery, generally between 6 and 24 h. Some stresses, such as those related to physical injury, can persist for weeks or even months. Reported changes in blood chemistry as a result of electrofishing include increases in adrenal hormones, lactic acid, and blood clotting agents which indicate overworked muscles and possibly traumatized tissues.

4. What are the physiological and anatomical effects of electrofishing on musculature, bone structure, blood, and reproductive organs?

Exposure of fish to an electric field of sufficient intensity results in various levels of central nervous system over-stimulation. The subsequent stimulation of muscles through the motor nerves, or lack thereof, causes the "behavioral" responses observed when electrofishing, e.g., taxis, narcosis, tetany. Under certain conditions, body muscles are stimulated to contract in very powerful convulsions. These and possibly tetany (a continuous convulsion) can result in trauma to vertebrae, associated bones, muscle, and blood vessels. Vertebrae and associated bones can be separated, compressed, fractured, splintered, or misaligned (Figures 1, 13, 15, 16). Muscles can be bruised and torn and blood vessels can be ruptured or blocked (Figures 1, 14). In extreme cases, such seizures can probably damage nerves and visceral organs. These internal injuries are often not obvious without X rays or necropsy. When present, external signs include abnormal swimming behavior, bent backs (Figures 2, 3), brands (Figure 4), and bleeding at the vent, gills, or base of the fins.

General consensus is that there is probably no significant effect of electrofishing on the development or function of the gonads or developing ova and sperm, except possibly when seizures are sufficiently severe to damage internal organs, including ripe (or near-ripe) ovaries. However, information on effects of electrofishing on reproductive organs is limited and based mostly on salmonid brood stock. Since fish are often targeted for sampling during the spawning season, the matter deserves serious investigation in wild fish, especially endangered species. In the wild, electrofishing stresses might also inhibit spawning in near-ready fish by altering behavior or physiology.

5. Are there differences in impact related to the age of the fish?

Yes. Early embryos have undeveloped neural and muscular systems, early larvae of many fish have incomplete skeletons and sensory systems, and all early-life stages are substantially smaller than later juveniles and adults. As a result, not only are specific electrogenic structures (nerves and muscles) affected by electrical fields either lacking or different than in older fish, but the organisms as a whole are subject to much smaller potentials or voltage drops across the body. Taxis and narcosis are obviously not possible in the earliest embryos, and vertebral damage is not possible in recently hatched larvae of many species, including the humpback chub and other cypriniforms. Other effects such as disruption of embryonic development, premature hatching, and even mortality at particularly sensitive stages can occur.

Because age is reflected by size in juveniles and young adults, there may be size-related, and therefore age-related, differences in susceptibility to electrofishing injuries. Some researchers have reported that injuries are more frequent among larger fish whereas others have found no consistent differences.

If poor condition is characteristic of very old fish of a particular species, these fish may be more or less sensitive to electric fields than younger cohorts of the same species. This matter has not been addressed in the literature.

6. Are there any differences related to the water quality?

Yes. Water chemistry affects the conductivity of water and the physiological condition of fish, both of which affect the threshold levels at which various responses occur. Also, very turbid waters make fish difficult to see and net, thereby reducing electrofishing efficiency and increasing the amount of time fish are exposed to the field. This in turn increases the probability of spinal injuries or deaths, many of which would go unnoticed.

7. Is there an impact from exposure time and electrical frequencies?

Yes. Exposure time in the zone of tetany is critical at least with regard to stress, exhaustion, and mortality. In full tetany, breathing ceases and death or damaging oxygen debt can quickly ensue. Mortality increases with duration of exposure. Fish must be removed from the zones of high field intensity as soon as possible and allowed to recover in well-oxygenated water.

With regard to spinal injuries, the only report on the effect of exposure time on injury suggests that it is not a significant factor, at least in AC or DC. This would be logical if, as has been suggested, spinal injuries are induced essentially when the field is established and perhaps when it is switched off. However, in PDC, injuries and mortalities increase with pulse frequency up to about 100 Hz (perhaps more); accordingly, increased injury with increased exposure time would seem a likely corollary. Pulse frequency also affects the degree of taxis and threshold levels for various responses. Optimal frequencies for these responses vary with species.

8. What influences the incidence and extent of injury to fish besides the shape of the electrical pulse, power density (field strength), and frequency of pulses? Is one parameter more influential than another?

Increased length of exposure in a state of tetany increases the percentage of mortalities. Fish position and orientation relative to an electrical field determine the voltage drop across the fish's body and the field-intensity threshold for various responses. They probably also determine whether a pulse is powerful enough to elicit a seizure and possibly cause spinal injuries. The possibility of detrimental voltage spikes when electric fields are switched on and off has been ignored because the duration of such spikes is believed to be too short to have an effect, but perhaps the matter should be reconsidered. Field intensity is probably the most important factor affecting mortality, but above a certain threshold, it might not be very important with respect to spinal injuries. Pulse frequency seems to have the greatest effect on spinal injuries; the number of fish injured usually increases with increased pulse frequency. Absence of pulses as in DC results in the least number of injuries, but they still occur (up to 30% in some rare cases). Also see response to question 9 below.

9. What is the threshold level of injury for each fish species and can this be identified?

Most adverse effects of an electrofishing field apparently result from two distinct conditions. The better understood condition is excessive exposure to tetanizing currents which can result in severe stress, fatigue, and cessation of respiratory activity, possibly leading to death. Whether the sustained contractions of muscles that define tetany are sufficient to cause spinal or related injuries, as previously assumed, has not been conclusively determined. The adverse effects of tetany can be minimized by determining minimal thresholds for tetany for the species and environmental conditions of concern and using these criteria to judicially select the power output and size, shape, and configuration of electrodes that will best limit the zone of tetany while still providing effective zones of taxis and narcosis. Unfortunately, measures necessary to reduce the zone of tetany sometimes require a corresponding reduction in overall size of the effective field. Also, specific field-strength thresholds for tetany have been determined for few species and these and other response thresholds vary with water temperature, conductivity, and probably size and physiological condition of the fish.

For fish that encounter the zone of tetany, it might be possible to define time limits for reasonably safe exposure in various levels of tetanizing currents. Exposure time can be reduced by modifying electrofishing technique and restricting use of the method to favorable conditions in suitable habitats. The maximum time a field is left on can be regulated to reduce the potential for overexposure of fish to tetanizing currents. A conscious effort should be made to quickly net fish in or approaching the zone of tetany.

The other electrofishing condition detrimentally affecting fish is one we have only begun to realize. It elicits sudden and very powerful convulsions of the body musculature. These seizures sometimes result in injuries such as compressed, broken, or misaligned vertebrae, other broken bones and joints, ruptured blood vessels, and possibly a host of other traumatized tissues and organs. Such injuries have long been attributed to tetanizing currents. Although based mostly on anecdotal information, it now appears that the electrical attribute resulting in such injuries can occur anywhere within, and possibly beyond, the effective field. In addition to the discussion below, see response to question 8 above.

We do not know whether these injuries vary consistently with distance from the electrode, i.e., with field intensity. If not, there probably is no field intensity threshold that would adequately reduce injuries while still permitting effective electrofishing. The injuries might even be more prevalent in the zone of taxis than tetany. If the minimum voltage-gradient threshold allowing injurious seizures extends beyond taxis into the zone of reactive detection, the twitches used in experiments to denote threshold levels for reactive detection could be just such seizures.

There appears to be substantial evidence that incidence of spinal injuries is associated with circuit closure and increases with pulse frequency. Accordingly some recent PDC waveform developments and recommendations involve reductions in pulse rates. However, taxis in PDC is also affected by pulse rate and can be inadequate for effective electrofishing when pulse rates are much less than 30 Hz. A pulse-rate threshold necessary to reduce injuries to an acceptable level might be too low for good taxis. Some researchers have suggested that the frequency of tail beats during taxis in PDC might be proportional to pulse frequency. Perhaps, as suggested by Haskell et al. (1954), taxis in PDC is itself the result of a regular series of related muscular convulsions alternating from side to side.

The initiation and severity of a seizure might depend upon the voltage differential created above a certain minimum as the current or individual pulses are switched on or off, the rapidity with which that differential is developed, and the orientation of the fish in the electric field (Haskell et al. 1954). If rapidity with which the voltage differential develops is a controlling factor, then pulse shape, particularly at the beginning of the pulse might be important. Pulse duration beyond a certain threshold required to allow a seizure does not appear to be a factor. If in DC, injuries are induced by switching the current on and off, attempts to minimize exposure to tetanizing currents by regulating "on" time and switching the current on and off more frequently, as suggested above, might be counter-productive and result in more injuries.

An associated possibility is that damaging seizures are caused or aggravated by voltage spikes that sometimes occur as pulses and currents are switched on and off. Some authorities maintain that these spikes are not sustained long enough to affect the nerves or muscles of fish. If spikes are determined to be a factor, they can probably be reduced or eliminated through modification to control box circuits.

The specific conditions causing these seizures, and differentiating between seizures that result in injury and those that don't, have yet to be defined. Sharber (pers. commun., also Sharber et al. unpubl. ms. 1991) suggested that such seizures are essentially the same as those experienced by humans and other animals with epilepsy or during electroconvulsive therapy. While the mechanisms involved are not thoroughly understood, a review of that work might facilitate our understanding of similar effects in fish and help channel research in a productive direction.

10. Is power density the main parameter associated with electrotaxis, narcosis, and injury, or are these physiological responses independent of each other?

Yes, field strength, whether defined in terms of power density, voltage gradient, or current density, is the prime electrical factor eliciting taxis, narcosis, and tetany. Once in a state of tetany, duration of exposure becomes the prime factor resulting in injurious fatigue or asphyxiation. However, as noted above, the switching on of pulses or current, rather than just field strength, appears to be the principal factor associated with spinal injuries. Taxis in PDC, when above a specific field-strength threshold, also appears to be a function of pulse frequency. Whether the seizures resulting in spinal injuries are independent of other responses is not clear, but such injuries are not restricted to the zone of tetany.

11. Does injury result from power densities that exceed those required for electrotaxis or that cause tetany?

Yes for some, no for others. Severe stress, fatigue, and hypoxia caused by excessive exposure to tetanizing currents can result in death or possibly long-term or permanent physical or physiological injury. Also, fish can be electrocuted or truly burned by extremely high field intensities or contact with an electrode. However, high field intensities are not prerequisite for spinal and related injuries caused by convulsive seizures. These injuries apparently can occur anywhere in the effective field and perhaps even in the outlying zone of reactive detection.

12. What is the relationship between narcosis and compression fractures?

There does not appear to be a specific relationship between the two effects. We don't know whether seizures resulting in compression fractures occur during narcosis. The same applies to tetany which is characterized by sustained contractions of muscles, unless these sustained contractions can themselves compress and fracture vertebrae.

13. Is there a relationship between injury and type of equipment used?

Yes. Adverse effects and mortality resulting from tetanizing currents can be reduced by minimizing the effective zone of tetany. This can be accomplished by enlarging the electrodes, reducing power to the electrodes, or using DC with it's higher threshold for tetany. Injuries resulting from momentary convulsions can be minimized by using DC rather than PDC or AC, reducing pulse frequencies in PDC to at least 30 Hz, or by using Coffelt's *CPS* or similar pulse trains. Pulse frequencies that are sufficiently high to effectively simulate DC or cause DC-like responses would also be expected to reduce the incidence of injury. If the rapidity with which pulses reach their peak voltage is a factor, use of waveforms with gradual rather than sharp rising pulses might reduce the incidence of injury. However, half-sine waveforms appear to be just as injurious as rectangular, quarter-sine, and exponential waveforms. Voltage spikes often occur when current is switched on or off and rises or falls very sharply (e.g., DC and the pulses in rectangular-waveform PDC). If such voltage spikes are a factor, they might be eliminated or minimized with electronic filters. But voltage spikes are not reported to be characteristic of half-sine waveforms and these waveforms appear no less injurious than others.

14. Is there an impact on eggs and developing alevins?

Possibly. Some investigators, particularly European authorities, have concluded that exposure to electric fields has no significant effect on developing eggs or larvae. But others have documented increased mortality as a result of exposure to electric fields. Egg mortality increases with both exposure time and field intensity. Eggs are most susceptible to mortality prior to the eyed stages but exposure late in the embryonic period might induce precocious hatching. Non-fatal developmental effects, aside from premature hatching, have not been investigated. Some biologists believe the effects of electric fields on eggs are similar to the effects of mechanical shock. Obviously, it would be prudent to avoid electrofishing over active spawning grounds, especially for endangered species.

There is little information on the adverse effects of electric fields on fish larvae and early juveniles but published observations suggest that some species are more sensitive than others (e.g., mortality more likely for pikeperch larvae than for trout larvae). Until we know how susceptible larvae of endangered species in the Colorado River Basin are to electric fields, it might be advisable to avoid electrofishing in active nursery areas as well as spawning grounds.

15. Can experiments be designed to quantifiably determine whether or not changes in an electrical system will reduce or eliminate spinal injury?

Yes. First, the prime factors involved in producing such injuries must be identified by controlled experiments. Then, electrofishing systems can be designed or modified to effectively eliminate or minimize those factors. Finally, the redesigned systems or modifications can be comparatively tested in still more controlled experiments.

16. Are there means presently used, or known in the body of literature that would reduce or eliminate injury to fish?

Yes. Where practical, use of well-smoothed or straight DC is the surest means to minimize spinal injuries and tetany-related effects. Researchers switching from PDC may have to adjust or modify their electrofishing operation to accommodate the much smaller effective field in DC. For example, some researchers working from boats use mobile or throwable anodes (Fredenberg 1992) to take advantage of DC taxis. However, there are some safety concerns that need to be resolved with this technique.

When using any current, tetany-related injuries and mortalities can be minimized by reducing the zone of tetany. This can be accomplished by prudent selection of electrode size, shape, and configuration, and reduction of power to the electrodes. Generally it is desirable to use the largest diameter anode or anode array practical for the waters being sampled. Cables should probably be avoided except when used as part of a multiple-dropper array. Cathode size should be as large as practical to minimize adverse effects in the cathodic field and reduce the resistance of the electrode system in water.

Sampling technique can be refined to minimize potential exposure to tetanizing fields and facilitate rapid removal of fish from the field. Restricting use of electrofishing to near optimal conditions (e.g., relatively clear and calm or smooth flowing waters) will enhance the ability of netters to quickly remove fish from the field. This not only reduces potential for excessive exposure of fish to tetanizing currents but should improve sampling efficiency. If DC is not practical and somewhat higher incidences of injury are acceptable, spinal injuries can be reduced in PDC by using pulse frequencies no more than 30 or 40 Hz (lower if practical) or specialized pulse trains designed for that purpose (e.g., Coffelt's *CPS*). However, pulse frequencies of about 20 Hz or less may not be effective in producing taxis. Although evidence on the injurious qualities of different PDC waveforms is not conclusive, quarter-sine and exponential waveforms should probably be avoided.

There is some evidence that the effects of AC, especially 3-phase AC, might not be as bad as its reputation, and that it is perhaps no worse than PDC with regard to spinal injuries. However, until proven otherwise, AC should be avoided, especially in work with endangered fishes. Because information on the relative effects of AC and PDC on spinal injuries is very limited, AC should be included in future research on such injuries. AC's negative reputation with regard to human safety also deserves consideration and should be evaluated. When taxis to the electrode is not critical and if its adverse effects can be minimized or accepted, as when specimens are killed or preserved, AC might still be a useful current.

17. What types of research identify the lower limits or thresholds for field strength and pulse frequency before efficiency (catch per unit effort) is reduced?

Controlled pond or field experiments. But laboratory studies can simplify experimental design by first identifying thresholds for various target species and size groups over a range of temperatures and conductivities for the waveforms to be tested. With this laboratory information and knowledge of conductivity and temperature conditions in the waters to be sampled, a range of potentially good electrofishing fields can be calculated and tested. Of course, the calculated electrofishing fields should be verified by actually mapping field intensities before proceeding with the experiments.

18. Are there threshold levels related to injury, and do these vary with species, sex, size, length, mass, etc.?

Yes, there are thresholds related to injury. Thresholds for tetanizing field intensity and lethal exposure times have already been approximated for some species. There is also a field-intensity threshold below which spinal injuries will not be induced, but that threshold has not been determined for any species and is likely to be near or below the threshold for taxis which is essential for effective electrofishing. Pulse frequency thresholds can probably be determined for various levels of injury in specific situations. As more is learned about the effects of other PDC attributes on the incidence and severity of injuries, thresholds regarding those factors will probably be identified. Thresholds, especially field-intensity thresholds, probably vary most with species, size (length or mass), and condition of the fish (see question "19" below).

19. How comparable are previous studies when most researchers don't have the ability to use an oscilloscope to distinguish the exact field strength?

Without an adequate set of in-water electric-field measurements, comparisons between studies, trips, or even sites within a trip can only be made on faith that the electrofishing controls and meters were in calibration and that everything was operating properly. Even when equipment is known to be functioning properly, few researchers, especially in field investigations, record sufficient information to allow an approximation of field size and intensity. Without a reasonable approximation of field intensity and size, and knowledge of the specific waveform, frequency, and duty cycle utilized, results can neither be related to field and current parameters nor properly compared with results from other studies or even different habitats within the same study.

Electrofishing fields can be mapped in detail or documented for a few consistently selected positions relative to the anode with in-water measures of voltage gradient. Voltage gradient can be measured with either a peak-value voltmeter or an oscilloscope connected to an appropriately designed probe. Although much more expensive, an oscilloscope offers more flexibility and allows the user to verify output voltage, waveform, frequency, and pulse duration. Using this information, control-box settings and electrodes can be adjusted immediately before each electrofishing event to minimize the zone of tetany around the anode or maintain similar-size fields at each sampling site.

Field intensity and size can also be approximated by calculation based on the waveform, frequency, and duty cycle used; peak voltage or amperage to the electrodes; size, shape, position, and configuration of all electrodes; and measures of water conductivity. Calculated fields are good for planning, but on-site, in-water measurements are necessary to verify actual intensity and distribution of the electrical current. In-water measures of field intensity are especially important if control boxes are not frequently checked and recalibrated.

20. What studies have been conducted regarding identification of delayed mortality resulting from electrofishing injury? What time frame have most fish been observed after exposure to an electrical field?

Several studies have held electrofished specimens for specified periods of time to assess delayed mortality (see above section on "Long-term Survival and Growth"). Time after electrofishing for most of these studies ranged from a day to several weeks; some recent studies, which have also monitored growth, have spanned several months to about a year. Except when fish were seriously injured or fatigued, most of these studies reported little long-term mortality specifically attributable to electric-field exposure.

Some fish and game agencies obtain brood stock by electrofishing and sometimes use the technique in other hatchery operations. Delayed mortality has not been reported to be a significant problem in these situations.

21. What species of fish have been used in electrofishing experiments?

Many species, including marine fishes, have been used in electrofishing experiments (see index to bibliography, Appendix 1). However, in most cases, results were not directly comparable between studies. Trout, particularly rainbow and brown trout, have been used most frequently. Among Colorado River Basin species, cutthroat trout, northern pike, common carp, goldfish, channel catfish, flathead catfish, bluegill, green sunfish, bluegill x green sunfish hybrids, largemouth bass, yellow perch, walleye, and mottled sculpins have been used in field, hatchery, or laboratory experiments. Almost all of these are non-native species. None of the endangered species of the Colorado River Basin, nor their close relatives, have yet been used in controlled electrofishing experiments.

22. Have there been any species of cyprinids other than grass carp and goldfish used in experiments?

Yes (see index to bibliography, Appendix 1).

23. Does injury occur at the onset of electro-narcosis or tetany or does it occur at the onset of body position in relationship to the field or at the point where the fish is introduced to the electrical field?

Spinal and related internal injuries resulting from convulsive seizures can apparently occur anywhere in the effective field (out to the threshold for taxis) and possibly beyond in the zone of reactive detection. We do not know the actual circumstances that cause these injurious seizures, but evidence to date suggests they are related to the switching on of current or individual pulses and the voltage differential experienced at that moment. The latter would certainly vary with the fish's position in the field and orientation with respect to the lines of current.

Tetany-related injuries and mortalities obviously occur after fish have reached the voltage-gradient threshold for tetany. They depend mostly on the degree of field intensity above the threshold (which varies with fish position and orientation) and the amount of time fish in are exposed to that field intensity.

24. Is injury a relationship of size, mass, length, and cross-sectional width, or is it species specific?

Based on field experiments in Alaska and Montana and controlled experiments elsewhere, there appear to be substantial differences in susceptibility of various species to spinal injuries caused by electrofishing. Assuming, voltage differential is an important factor in causing such injuries, all aspects of fish size (e.g., length, width, surface area, mass, and volume) should probably be related to electrofishing-induced spinal injuries. But recent field studies on electrofishing injury indicate no significant size-related difference in injury frequency or severity among electrofished rainbow and brown trout between 20 and 58 cm TL. Such injuries were also observed among fish less than 20 cm TL, but data were insufficient for analysis of size-related differences. The relationship between size and mortality is less clear, but in at least one controlled experiment, size was not found to be a critical factor.

FUTURE RESEARCH

A better understanding of the mechanisms involved in the various responses to electric current, including injury, might result from a review of the effects of electric currents on humans and other animals. Sharber (pers. commun.) suggests that the principal responses, which he considers as phases of epilepsy, are essentially the same for all vertebrates, fishes included. However, even the mechanisms involved in producing epileptic responses in humans and other animals are not fully understood. Discrepancies between the Bozeman and Biarritz paradigms must be resolved. Much more laboratory experimentation will probably be required to better understand these mechanisms, various factors which affect them, and the injuries caused by them. Among past laboratory experiments to specifically document fish responses in electric fields and thresholds for them, either there was no mention of aftereffects (perhaps there were none), or few aftereffects were reported (e.g., "all but one fish recovered rapidly and behaved normally"—Kolz and

Reynolds 1989). However, as in field investigations, fish usually were not examined by X rays or necropsy.

There is obviously a need to proceed with very intensive experimentation to resolve many unanswered questions and define specific and reliable means for minimizing electrofishing injury. This need was anticipated in the Bureau of Reclamation's three-phase recommendation for gathering information needed by the National Park Service and researchers working in the Colorado River Basin. Because the problems addressed in the research recommendations below are not unique to this region, but rather are quite universal, the results of Phase II and eventually Phase III will be valued by researchers using electrofishing gear throughout the country and probably much of the world. But this work will be limited and can only explore responses and effects of selected electrofishing currents on a few species of fish. We may not be able to reasonably extrapolate the results to vastly different species, currents, and situations anymore than we can at this time extrapolate our observations on rainbow trout to the humpback chub.

Perhaps it is time for a concerted, well-funded, national or international effort to better document electrofishing effects and injuries. Such a coordinated effort will probably require leadership by a federal agency with a vested interest (e.g., U.S. Fish and Wildlife Service or Bureau of Reclamation); a consortium of state, federal, or international (FAO, EIFAC) agencies; or a major professional organization such as the American Fisheries Society. We must better understand the problem, the factors involved, and how to minimize the adverse effects. Where electrofishing injury is a problem and we cannot adequately reduce the extent of injury, we must abandon or severely limit use of the technique and seek less damaging alternatives. As fishery biologists, this is our ethical responsibility to the fish, the populace we serve, and ourselves.

RECOMMENDATIONS

INTERIM POLICY TO MINIMIZE ELECTROFISHING INJURY

J. H. Davis, Superintendent of Grand Canyon National Park suggested in a 12 July 1990 memorandum to the GCES project manager that electrofishing for humpback chub be kept to a minimum and conducted in such a way as to minimize possible stress and injury. This suggestion remains warranted and should be extended to all endangered and native species until the adverse effects on those species are adequately documented and understood for more definitive policy. Based on the preceding review, the following measures are recommended for interim policy:

I. Until proven otherwise, assume that presently used and available electrofishing techniques can cause enough injury to endangered (or incidental) species to be a serious concern.

II. Consider alternatives to electrofishing in ongoing programs if those alternatives are practical, not likely to cause enough injury to be a serious concern, and not likely to jeopardize critical comparisons with past data.

A. The bibliography in Appendix I lists approximately 80 references with information comparing electrofishing with other collection techniques. However, most of these sources compared sampling efficiency rather than injurious or adverse effects. A review of this comparative literature would be useful, especially with regard to adverse effects.

B. Judgements regarding the injurious effects of alternative gear may have to rely, at least in part, on the experiences of biologists involved in the project or outside contacts. Unlike non-fatal and often unapparent electrofishing injuries, injuries caused by most other gear are external and more easily observed.

C. Injuries caused by alternative capture techniques may be more easily controlled than those caused by electrofishing. For example, attending trammel nets or trap nets every 15 or 30 minutes rather than every couple hours or overnight should substantially reduce mortalities, extreme stress, and external injuries.

III. Unless immediately critical to the recovery effort, limit use of electrofishing in new sampling programs by substituting alternative techniques that are not likely to cause enough injury to be of concern, or delay decisions to implement new programs relying on electrofishing until the injurious effects of the technique are adequately documented. Exceptions would include field investigations designed specifically to assess the adverse effects of electrofishing.

IV. If after considering recommendations II and III above, electrofishing remains the only reasonable capture technique:

A. Based on the latest available information, update electrofishing equipment and procedures, including specimen handling, to assure the least harm to captured fish, while maintaining necessary comparability with past data.

1. Use the least harmful current available for effective capture of target fish.

a. Where practical, use DC.

(1) Although use of DC will not eliminate the possibility of spinal injury in fish, the incidence of such injuries is usually much less than with PDC or AC.

(2) If produced from an AC source, DC should be well filtered to minimize ripple.

(a) Strongly rippled DC might function somewhat like PDC (or a hybrid DC-PDC waveform) and possibly result in a greater number of injured fish than a smoother, well-filtered DC.

(b) The degree of ripple in a DC current can be determined or verified with an oscilloscope.

(3) Because of significantly higher field-intensity thresholds for desired responses, use of DC requires either a more powerful generator or acceptance of a smaller effective field.

(a) Some of this limitation might be overcome by altering electrofishing technique and taking advantage of DC's reputation for good anodic taxis.

(b) Experimental mobile or throwable anode techniques represent such innovative approaches and are reported to be effective (Nehring 1991; Fredenberg 1992), but they cannot be recommended until serious safety concerns are resolved (Sharber pers. commun.).

b. If DC is not practical, use PDC systems with waveforms, pulse frequencies or patterns, and power levels likely to cause the least damage while still maintaining adequate capture efficiency.

(1) Rectangular waves with pulse frequencies no more than 40 Hz, preferably 30 Hz or less, if effective, or Coffelt's *CPS* are presently recommended in this regard. However, much research is still needed on these and alternative currents.

(2) Smith-Root's *P.O.W.* system may allow the user to experiment with and configure alternative pulse patterns to reduce the incidence of spinal injuries.

c. Whether warranted or not, AC is recognized by many authorities as the most harmful waveform used in electrofishing. Until proven otherwise, AC should be avoided for most purposes.

(1) AC should only be considered when fish are to be killed and injury or mortality to uncaptured fish is not a concern.

(2) Fish response to AC is not appropriate for boat

electrofishing or any situation in which anodic taxis is desired.

2. Operate electrofishing systems at the lowest effective power setting with the largest practical anode(s) to minimize or eliminate the zone of tetany around the anode.
   a. Spherical, circular, or dropper array anodes are generally recommended over cables (especially single or paired, small-diameter cables).
   b. Equipment for measuring conductivity and field strength (voltage gradients) in the water should be available on each electrofishing trip to monitor equipment operation and adjust settings and electrodes for the desired size and intensity of the field.
      (1) For in-water measures of field strength, portable, field-durable, oscilloscopes may be preferred since they can also be used to monitor output waveforms and pulse duration, but commercial field-strength meters or similar home-built units based on voltmeters should be adequate if they accommodate the specific waveforms used.
      (2) Field-strength measurements should be based on peak voltages. If the meters used can only measure average voltages, then pulse frequency, width, duty cycle, and shape can be used to approximate peak voltages.
   c. Control-box settings and electrode selection should be based on predefined field sizes and intensities for the target species and size group. These fields should be defined to take advantage of probable species- and size-specific voltage-gradient thresholds to maximize taxis and narcosis while minimizing the zone of tetany.
      (1) Control-box setting and size of the electrodes should be determined by calculation or, preferably, by in-water voltage-gradient measurements, not by on-the-spot experimentation.
      (2) Specific threshold criteria for endangered species should be determined in controlled experiments. Until then, they will have to be approximated using threshold data available for other species and size groups.
      (3) Smaller zones of tetany should result in fewer incidents of electrocution, respiratory disfunction, severe stress, and severe fatigue.

3. Adjust electrofishing technique in such a way as to net and remove fish from the electric field as soon as possible.
   a. Select and position anodes such that fish are brought as near to the surface and as close to the netters as possible before narcosis. Maneuver the boat with the current in such a way as to improve netter access to the fish.
   b. Position netters and lighting at night such that fish are more easily observed and captured; use polarizing glasses and other aids to minimize glare and reflections when electrofishing during daylight.
   c. Avoid electrofishing when waters are rough or excessively turbid.

4. Optimize fish holding facilities for fast recovery and least possible stress.
   a. Fresh, well-oxygenated water must be provided with a temperature similar to that from which the fish were removed. Consider installation of a wire-mesh, faraday-shield live tank through the bottom of electrofishing rafts or boats not used as cathodes (Sharber and Carothers 1987).

   b. Avoid overcrowding captured specimens.
   c. Some researchers suggest use of an anesthetic, such as MS-222, to keep fish calm while they recover or are processed (including X rays). However, care must be taken to assure that the anesthetic itself does not interfere with recovery. It might be wise to use the anesthetic only in a second container for fish that have recovered equilibrium and normal behavior. (Note that some anesthetics, including as MS-222, can only be used in accord with U.S. Food and Drug Administration regulations.)

B. Assure that electrofishing equipment is well maintained and in prime operating condition, and that personnel are adequately trained in its use and emergency procedures. Properly used equipment and attention to safety should minimize injury to fish and crew.
   1. National, state, or more comprehensive and up-to-date guidelines for safe and proper use of electrofishing equipment should be adopted and closely followed. Guidelines presently available through the U.S. Fish and Wildlife Service (1985) are reproduced in Appendix V; also see Goodchild, (1986, 1990, 1991).
   2. Because boat electrofishing gear are subject to extreme conditions, an oscilloscope (or other appropriate diagnostic equipment) should be used to check electrofishing components for proper operation and calibration before and periodically during each electrofishing trip.
   3. Electrofishing-team leaders should be properly trained and certified in the theory and practice of electrofishing equipment and techniques.
      a. An appropriate course and certification program is available through the U.S. Fish and Wildlife Service Fisheries Academy–Leetown, Kearneysville, West Virginia. Similar courses or related text material may be offered by state agencies, universities, or manufacturers.
      b. Such courses should be frequently updated to provide the latest information on equipment and techniques for minimizing adverse effects (e.g., injury) on fish and other aquatic organisms. The Fisheries Academy of the U.S. Fish and Wildlife Service, which maintains a registry of biologists certified in electrofishing, should be encouraged to forward to certified biologists bulletins of the latest recommendations for minimizing injury (and other advances) as that information becomes available.
   4. Other electrofishing team members should be trained, if not certified, in the proper use of electrofishing gear and techniques for the specific sampling program (perhaps by the team leader each season).
   5. At least two, if not all, team members should be prepared to handle medical emergencies through advanced planning for each trip (procedures and means to get help or reach medical facilities) and certified training in first aid and CPR (cardio-pulmonary resuscitation).
   6. Re-certification for electrofishing, first aid and CPR should be required on a periodic basis, perhaps every 5 years to assure electrofishing teams of the latest information.

C. Institute standardized procedures for documenting each electrofishing event including output parameters, water conductivity, water temperature, and field strength (voltage gradient at specified distances from the anode) as well as detailed observations on injuries or abnormal behavior among individual specimens. Mortalities of all species should be frozen or preserved for subsequent examination. This information is necessary to compare results between sites and studies, evaluate the conditions under which harmful effects continue to occur, and refine techniques to further reduce harmful effects.

RESEARCH ON ELECTROFISHING INJURIES AND RESPONSES

The following are recommendations for Phase II of the Bureau of Reclamation's three-phase plan for assessing the potential for electrofishing injury to endangered and other native fishes in the Colorado River Basin, ascertaining specific causes and means for minimizing adverse effects, and establishing policy on use of electrofishing in endangered species research and monitoring programs. This report is the culmination of Phase I. Phase II will consist of controlled laboratory and field experiments to answer questions unresolved by past research. If the potential for electrofishing injuries is significant and changes in equipment and technique are recommended to sufficiently reduce that potential, Phase III will test those recommendations in practical field operations. Modifications of the following Phase II recommendations may be useful for similar concerns elsewhere.

Some of the suggested research parallels studies previously conducted for other species, particularly rainbow and brown trout. Accordingly, for comparative purposes, rainbow trout are often recommended as one of the test species.

The first question is whether the species of concern are significantly injured by present electrofishing programs and techniques. If not, the matter of electrofishing injury to endangered fishes in the Colorado River Basin becomes a "non-problem", and further research either becomes unnecessary for recovery concerns or can be redirected toward other basin fishes that may be significantly affected. Because endangered species recovery requires consideration of the entire ecosystem and all participants in the community, adverse effects of electrofishing on other native species are also a concern. Even in cases where electrofishing injuries are likely to be significant, some injury might be considered acceptable if there are no better alternatives for obtaining information critical to recovering endangered populations.

I. Determine whether and to what extent electrofishing gear and procedures used in the Colorado River Basin cause physical injury to endangered or other native fishes. The three suggested approaches to this matter are intended to provided complementary information, but if necessary they could be treated as alternatives. For example, if the first approach (A) is logistically impractical, precluded by interim policy on use of electrofishing in ongoing programs, or if use of X-ray radiography is found harmful to fish or their offspring, the second approach (B) can serve as a reasonable alternative. The third approach (C) could substitute for both the first and second, but it is based on hatchery fish which may be less sensitive than wild specimens.

A. If ongoing studies continue to utilize electrofishing as a capture technique, include X-ray analysis for vertebral damage and examination for external signs of injury as part of specimen processing for endangered and other selected species. Fish captured in these programs are usually processed and returned alive to the system.
   1. Determine whether X-ray radiography adversely affects fish or their offspring.
      a. Conduct an intensive search of the literature. In a cursory search, I have found no pertinent information for fish.
      b. Assuming information from the literature is inadequate, conduct laboratory experiments to determine if the maximum X-ray doses likely to be administered cause significant harm to fish, their reproductive potential, or their gametes (e.g., abnormal genetic mutations).
         (1) The developmental state of the gonads at the time of X-ray exposure might be an important consideration in experimental design.
         (2) Unless genetic analyses themselves can provide the needed information, these experiments probably require the monitoring not only of the exposed fish through spawning, but their offspring through larval

development or, preferably, the next generation.

(3) The results for any test species (e.g., fathead minnow *Pimephales promelas*) can be extrapolated to other species, but for greatest certainty, the endangered species themselves (i.e., hatchery stock), or closely related surrogates, should be utilized in these or follow-up experiments.

2. Assuming the X rays are not found to be harmful, document the presence and severity of spinal injuries according to Reynolds' (unpubl. ms. 1992) criteria for X-ray analysis (Table 4).
   a. Supplement the usual field crews with a separate team of properly trained and equipped researchers to expedite field X-ray procedures and assure the safety of associated personnel. Portable X-ray machines are available for under $5,000.
   b. Less obvious vertebral fractures may be difficult to assess in X rays of small fish.
3. Document and describe in detail external signs of physical injury (e.g., brands; bent backs; bleeding at the vent, gills, fin bases, or elsewhere) and abnormal behavior. Also record water temperature, conductivity, turbidity, depth, and other environmental conditions; electrofishing configuration, settings, waveform, frequency, time, and strategy (approach); and in-water measurements of field strength at standardized locations relative to the electrodes and vessel. Such documentation should be standard practice for all electrofishing operations regardless of purpose.
4. Necropsy all electrofishing mortalities, specimens that are not likely to survive, specimens sacrificed for other purposes (e.g., contaminants analysis), and, if feasible, statistically useful subsamples of selected non-endangered species.
   a. Document spinal damage and associated hemorrhages according to Reynolds' (unpubl ms. 1992) criteria for X-ray analysis and fillet-based necropsy (Table 4).
   b. Document other external and internal damage or anomalies according to Goede and Barton's (1990) necropsy-based procedures and criteria for fish health and condition profiles (HCP; the blood tests can be deleted for purposes of these investigations).
   c. Except for certain aspects of HCP and observations of external signs of injury and abnormal behavior, these fish can be iced or frozen and processed elsewhere at a later time.
5. Tag each fish X ray to assure that the recorded information can be traced back to the specimen of origin. For released fish, this information can then be associated with subsequent recapture data.
6. If the same species and size classes are collected in existing programs by other gear, they should be similarly examined and documented as controls and for comparison.
7. Evidence indicates that trout are especially susceptible to spinal injuries; if captured in sufficient numbers, they should also be analyzed for comparative purposes.

B. Conduct a special field study, independent of ongoing investigations, to document the incidence and severity of electrofishing injuries in selected fishes, especially native species chosen as surrogates for the endangered species (e.g., roundtail chub and flannelmouth sucker *Catostomus latipinnis*).
   1. Electrofishing gear and techniques should be similar to those normally used in the basin.
   2. Document and describe in detail abnormal behavior and external signs of physical injury.
   3. Sacrifice, X ray, and necropsy all target species or statistically useful subsamples by size class. Follow the procedures

outlined above for mortalities and sacrificed fish (I.A.4.a-c). X rays could be taken by a cooperating educational or medical facility.

C. Conduct controlled electrofishing experiments in large ponds to document incidence and severity of electrofishing injuries on hatchery-reared endangered fishes, preferably fish not previously subjected to electric fields.
   1. Fish should be uniquely tagged for individual identification and documented for pre-existing injuries or anomalies based on X rays and detailed external examination.
   2. Electrofishing gear and techniques should be similar to those typically used in the field.
   3. Fish captured by electrofishing should be observed for abnormal behavior and examined for external signs of injury, then sacrificed, X rayed, and necropsied according to procedures outlined above for mortalities and sacrificed fish (I.A.4.a-c).
   4. Fish remaining in the ponds after electrofishing should be collected by other means (e.g., seining) as soon as possible and similarly processed for comparison. These specimens represent fish that were subjected to electrofishing fields but escaped capture.

II. Conduct laboratory experiments to document and compare the injurious effects and induced responses of currently used and potentially less harmful electrofishing waveforms on endangered fishes (or surrogates) and other species of concern in the Colorado River Basin. Identify waveforms, field characteristics, and conditions (from among those tested) that will minimize injurious effects but still elicit sufficient taxis and narcosis for effective electrofishing.

A. Currents and waveforms to be tested.
   a. Currents and waveforms typically used in the Colorado River Basin or believed to reduce the incidence of injury.
      (1) Rectangular 80-Hz PDC with 5-ms pulses (40% duty cycle).
      (2) Rectangular 60-Hz PDC with 4-ms pulses (25% duty cycle).
      (3) Rectangular 30-Hz PDC with 4-ms pulses (12% duty cycle).
      (4) Coffelt's *CPS*, a pulse train of three 240-Hz, 1.6-ms pulses every 15th of a second (7.2% duty cycle).
      (5) DC (filtered and conditioned from rectified AC)
   b. 60-Hz AC should ultimately be tested for comparative purposes.
   c. Others of interest.

B. Variables to be considered in experiments with each waveform. Except for field intensity, initial experiments should be conducted with these variables held at a fixed level that approximates typical conditions when electrofishing in the Colorado River. Subsequent experiments should be conducted over a range of values for each variable (at least two more levels), one variable at a time, to assess the effect of those variables on injuries and responses.
   1. Field intensity (voltage gradient) and exposure time.
      a. Experiments should be run with voltage gradient increased at a steady continuous rate from a near zero value. Individual tests should be concluded at a particular response level (from reactive detection to full tetany and electrocution) and fish examined for injuries at each of these response levels. At least in initial or preliminary experiments, different rates of voltage gradient increase should be tested (thereby increasing or decreasing exposure time). These experiments simulate an electric field gradually moving over a fish.
      b. Experiments should be repeated over a range of specific voltage-gradient levels for a range of exposure times; the current should be switched on and off after the fish are appropriately positioned in the water. These experiments simulate

a stationary electric field positioned over a fish when it is switched on.

2. Water conductivity between 10 and 2,000 µS/cm; 500 µS/cm would be a good choice for initial experiments.
3. Water temperature between 5 and 25°C; 15 or 20°C would be a good choice for initial experiments.
4. Fish size groups between 2 and 50 cm. Since fish under 10 cm are usually easier to handle and obtain in quantity, they might be a good choice for initial experiments. However, they may be more difficult to necropsy and their X rays may not be as easy to analyze as for larger fish.
5. Fish orientation. Experiments should be conducted with fish initially oriented (or maintained) in various directions (e.g., toward the anode, toward the cathode, transverse to both, and positions between these). Position or changes in position during an exposure could significantly affect experimental results.

C. Fish species.
   1. Initial experiments should be conducted on surrogates for the endangered species and rainbow trout, the latter for comparison and verification of previous observations on that species.
   2. Once the critical ranges for experimental variables are narrowed as a result of the initial experiments, more focused experiments can be conducted on other species, including endangered species if expendable hatchery-reared specimens are available. If the effects, responses, and response thresholds for the endangered species are very similar to those for the surrogate species, only enough endangered-species experiments need to be conducted to support that conclusion and remaining surrogate-species results can be extended to the corresponding endangered species.
   3. If differences in response thresholds and susceptibility to injury are found between hatchery-reared and wild stocks of the same species, these differences should be documented and considered in the interpretation of results. Such differences have been observed for trout (Sharber pers. commun.; Fredenberg pers. commun.).

D. Each experimental specimen should be tagged for individual identification, measured, examined for external anomalies, X rayed (to document any existing spinal anomalies), and acclimated to the water temperature and conductivity in which it will be tested.

E. Responses for each tested fish should be recorded on video tape with specimen data, a time index, and the level of variables tested. Such documentation will allow independent analyses.

F. After each trial, fish should be observed carefully for abnormal behavior, rate of recovery, and external signs of injury, then X rayed for spinal injuries and dissected for related internal injuries according to the procedures outlined above for mortalities and sacrificed fish in field experiments (I.A.4.a-c).

G. Experiments should be initially conducted in homogeneous fields (rectangular tank with full cross-sectional electrodes) to minimize confounding factors and allow comparison with published data. When waveforms and other experimental factors significantly affect either injuries or typical responses, experiments should be repeated in heterogeneous fields (e.g., quarter-circular tank with one full-depth electrode at the apex and the other full-depth electrode lining the outer wall, or perhaps in an open-water setting such as a pond with standard electrofishing electrodes).
   a. In heterogeneous fields, fish should be tested in both anodic and cathodic fields. Effects in the cathodic field have been largely overlooked in past research, especially with regard to injury, and they may differ from effects in the anodic field.
   b. These experiments will establish the relationship between responses and

thresholds observed in homogeneous and heterogeneous fields.

(1) If the relationship is well defined and consistent, future experiments with other species may only need to be conducted in homogeneous fields.

(2) If the relationship is inconsistent or difficult to define because of continuously varying voltage gradients, future experiments for field-applicable thresholds may be limited to heterogeneous fields.

H. If these experiments demonstrate that some electrofishing currents, waveforms, and conditions are less harmful to endangered or surrogate species than others while still eliciting sufficient taxis and narcosis for effective electrofishing, then electrofishing gear and techniques should be modified accordingly. Based on response threshold data, it might also be possible to define optimal field sizes and intensities to minimize harm and facilitate consistent electrofishing effort over a wide range of water conductivities and temperatures. A simplified set of experiments could be recommended for similarly determining optimal electrofishing fields for other species.

III. Conduct a series of experiments on the effects of presently used electrofishing fields, or recommended modifications, on the spawning and early-life stages of endangered species (or surrogates), other native species of concern, and rainbow trout (for comparison with existing observations).

A. Determine the adverse effects of electrofishing fields on the reproductive capability and behavior of fish exposed while in or approaching a state of spawning readiness. Fish are often targeted for electrofishing as they stage, aggregate, or begin spawning.

B. Determine the effects of these electrofishing fields on developing eggs and larvae (in and out of simulated substrate). Adults are sometimes electrofished over spawning grounds.

C. Document responses and response thresholds of protolarvae, mesolarvae, metalarvae and early juveniles and determine the sizes at which these fish begin to respond like older fish and spinal injuries occur. Larval and YOY juvenile fish are likely to be present in some habitats that are electrofished for larger juveniles and adults.

IV. If electrofishing-induced spinal injuries are a problem for endangered species, and changes in technology (e.g., current and waveform) still result in a significant number of injuries, then conduct a series of 1-year or longer pond investigations to assess subsequent effects on survival, growth, condition, and, if possible, reproductive viability.

A. Each pond should include approximately equal numbers of treatment and control fish.

B. Treatment fish would be intentionally injured (vertebral fractures or misalignments) by electric fields and X rayed for subsequent comparison. Also consider a second set of treatment fish, those subjected to the electric field but not sustaining a detectible injury.

C. All fish should be periodically captured by non-electrofishing techniques and monitored for injury healing, survival, growth, condition, and reproductive state.

D. If most electrofishing-induced injuries do heal and subsequently have no detectable effect on survival, growth, condition, or reproductive behavior, then perhaps the matter of electrofishing injuries is not critical with respect to population management and recovery of the species.

E. It might be desirable to conduct these experiments even if changes in standard electrofishing technique do reduce the harmful effects; the results might help assess the extent of damage done to endangered populations by past electrofishing activities.

V. Based on available information on the effects of electricity on fish and other vertebrates, design and conduct laboratory experiments to determine or confirm the specific causes and mechanisms involved in electrofishing injuries and responses.

A. To complement the review herein and pertinent publications listed in the appended bibliography, consult with vertebrate electro-physiologists and review the effects of electricity on other vertebrates (including man), the mechanisms involved, and their relationship to epilepsy.
B. If feasible, electro-physiologists should be consulted or employed in the planning, review, or conduct of these experiments.
C. Evidence to date suggests that for fish subjected to an electric field of sufficient strength, spinal injuries and taxis in PDC are probably caused by abrupt changes in voltage differential as when current is switched on and off or pulsed. Accordingly some experiments should be designed to test this hypothesis and explore the aspects of electrofishing currents and fish responses associated with it.
D. Factors that might be considered include the degree of voltage change required (field intensity), rapidity with which that change must occur (pulse shape or waveform), duration of the current or pulse, frequency with which current is changed (pulse frequency in PDC), the effect of voltage spikes, and interactions between these and other factors.

VI. Based on results of the above suggested research, refine or develop new electrofishing gear and techniques to help minimize adverse effects and maintain the effective size and intensity of the field. Some possibilities for future refinements and developments in boat electrofishing are outlined in Appendix VI.

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APPENDIX I

Indexed Bibliography of Electrofishing Literature

INDEXED BIBLIOGRAPHY OF ELECTROFISHING LITERATURE

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CONTENTS

INDEXED BIBLIOGRAPHY OF ELECTROFISHING LITERATURE

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This topically indexed bibliography of 854 references was prepared for a review of fish injuries and mortality caused by electrofishing and the various factors associated with those impacts. The bibliography is extensive but not comprehensive, especially with regard to older non-English literature, most of which is included in bibliographies by Meyer-Waarden et al. (1960), Shentiakov (1967), and Halsband and Halsband (1970; 1980). Emphasis in the index is on effects on fish and factors affecting fish response to electrical fields, but other aspects of electrical fishing gear and techniques also are covered. Over a third (315) of the entries are recent, published in 1980 to 1991; the rest are distributed temporally as follows: 246 for 1970 to 1979, 146 for 1960 to 1969, 119 for 1950 to 1959, 14 for 1930 to 1949, 5 for 1900 to 1929, and 6 for 1859 to 1899. A substantial portion of the electrofishing literature in this bibliography is "gray" literature. Non-serial government or private firm reports, conference or symposium abstracts, and other technically unpublished documents (mimeo or photocopy) may contain useful information but copies are often difficult to locate.

Bibliographic entries are in the format specified for journals of the American Fisheries Society including use of full, unabbreviated (with few exceptions) source information to avoid ambiguities and facilitate acquisition. Serial titles follow *Serial Sources for the BIOSIS Database*, titles for serials not covered by that document were verified elsewhere. Titles for non-English publications were handled as follows: An English translation of the title is unbracketted when it is provided in the original publication (often in association with an English abstract or summary). When a title translation is not provided in the publication, the translation is bracketted and followed by the original title if it is in a language using the Roman alphabet and available through our sources. Language of the publication and inclusion of an English abstract or summary are indicated in brackets following the title.

The bibliography was compiled largely by consolidating selected references from previously published bibliographies and articles, CD-ROM (Aquatic Sciences and Fisheries Abstracts, World Wildlife Review, National Technical Information Service) and online (Colorado Alliance of Research Libraries, Biological Abstracts, Zoological Record, and Dissertation Abstracts) computer databases, and searches requested of the U.S. Fish and Wildlife Service in Fort Collins (Fisheries Review database) and the Fish and Wildlife Reference Service in Bethesda, Maryland. With the generous help of Colorado State University Library science-reference and inter-library-loan staff, we acquired copies of or examined much of the literature. As time and resources allowed, we verified, corrected, or completed bibliographic data obtained from our various sources. Still, bibliographic information for some entries remains incomplete (usually denoted by a question mark in brackets), and some errors likely persist. Publications on (or believed to be on) studies using electrofishing techniques but not relating directly to electrofishing itself ("use only") were deleted from this bibliography. All records are maintained in a bibliographic database under *Reference Manager* (a program provided by Research Information Services, Inc., Carlsbad, California). In the future, we intend to make the electrofishing portion of our database files available for use by others.

The most comprehensive source of references, particularly for recent electrofishing literature, is the extensive indexed bibliography at the end of one of two recently published books emanating from the symposium on "Fishing with Electricity" held in Hull, England in April 1988 (Cowx and Lamarque 1990, *Fishing with Electricity, Applications in Freshwater Fisheries Management*). This 931 reference bibliography by Burridge et al. (1990) also serves as the literature-cited section for the book; perhaps for this reason, at least 25 entries do not relate directly to electrofishing (most of these publications concern data analysis and sampling design) and over 100 references are (or appear to be) about studies in which electrical fishing gear was used but do not concern electrofishing itself ("use-only"). Also included, but without page numbers, were 1988 symposium papers expected to be part of the companion volume (Cowx 1990a, *Developments in Electric Fishing*); however, a few of these papers are either not in the final publication or not included under the same titles. To save data entry time for most of the references included in our bibliography, we requested and received from G. A. Goodchild a copy of the *dBase* file that he and his associates (M. E. Burridge and C. L. Rutland) used to compile their bibliography. As they intend to update their bibliography periodically, we will reciprocate.

We considered treating this bibliography as an addendum to the Burridge et al. bibliography (i.e., listing only new or additional references), but matters concerning effects of electrofishing or electrical fields on fish and the various factors involved were indexed under only one category, "Effects on Fish and Other Animals." Our need for more detailed indexing on these matters, including a taxon index, and the need to correct or complete source information for some entries in the Burridge et al. bibliography necessitated the listing and indexing of all pertinent references. Since references on electrofishing or related matters not pertaining to effects on fish are also in the database, and since these references may be useful to some recipients of the bibliography, we included and appropriately indexed all electrofishing literature in our database files except that considered "use only." For purposes of comparison, this bibliography includes 728 references also included in Burridge et al. (71 Burridge et al. citations are problem entries we did not have time to address—many may eventually be added to our database). In addition, our bibliography includes 136 entries not in Burridge et al., 44 of which are for the years 1989 to 1991 (including the nine chapters in Cowx and Lamarque 1990).

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Serafy et al. 88
Shilenko 80
Simonaviciene 87b
Stewart 81
Szatybelko 79
Tester 52
Blancheteau 67
Cross and Stott 75
Daniulyte et al. 87
Dodson 61
Hale et al. 84
Klima 74
Loeb 57
Maiselis and Shabanov 75
Maksimov et al. 87
Maxfield et al. 59
McClendon and Rabeni 86
McLain et al. 65
Mishelovich 75c
Mitra and Biswas 69a
Morgan 53
Newman 59
Paragamian 89
Pyatnitskiy and Stepanova 86
Rollefson 58a
Seidel and Klima 74
Shabanov 75
Shilenko 83
Smith 78
Stewart 90b
Tauchi 31
Trofimova 84
Carr 68
Curry and Kynard 78
De Groot and Boonstra 70
Flux 67
Haskell et al. 54b
Latta and Myers 61
Lukashov and Usachev 63
Maksimov 75
Malkevicius and Toliusis 87
Maxfield et al. 69
McLain 57
McMillan 28
Mishelovich and Aslanov 90
Mitra and Biswas 69b
Morris and Novak 68
Nusenbaum and Faleeva 61
Peduzzi and Meng 76b
Rauck 80
Rollefson 58b
Seidel and Watson 78
Shentiakov 60
Simonaviciene 87a
Stepanova 82
Stewart and Cameron 75
Taylor et al. 57
Viaud and Dreyfus 57

Whaley et al. 78
Yundt 83a
Yundt 83b
Zalewski 83
Zhong 90

Physiology (only):

Covers physical and passive responses (other than or in addition to physical injury or mortality), such as narcosis or anesthesia, tetany, and biochemical changes in blood or muscle. Also see "Both Behavior and Physiology" below and "General" above; articles listed under "Undetermined" below might also be pertinent.

Adams et al. 72
Barham and Schoonbee 90
Barham et al. 88a
Barham et al. 88b
Barham et al. 87
Barham et al. 89a
Barham et al. 89b
Bird and Cowx 90
Biswas and Karmarkar 79
Bodrova and Kraiukhin 60
Bouck and Ball 66
Bouck et al. 78
Burns and Lantz 78
Charbonnel-Salle 1881
Chmielewski et al. 73a
Edwards and Higgins 73
Ellis 74
Fisher 50
Gatz and Adams 87
Gatz et al. 86
Gosset 74
Gunstrom and Bethers 85
Halsband 77
Hartley 67b
Haskell 40
Hauck 49
Horak and Klein 67
Hudy 84
Hudy 85
Jesien and Hocutt 90
Kazlauskiene 87
Kazlauskiene and Daniulyte 87
Kolz 89a
Kolz 89b
Kolz and Reynolds 90
Lamarque 76a
Lewis and Charles 58
Luczynski and Kolman 87
Madden and Houston 76
Marriott 73
Maxfield et al. 71
Monan and Engstrom 63
Nakatani 55
Namboodiri 66
Namboodiri and Verghese 69
Orsi and Short 87
Scheminzky 34
Scheminzky 36
Schneider 89
Schreck et al. 76
Shentyakova et al. 70
Shetter 38
Shparkovsky and Vataev 85
Sloley et al. 86
Stewart 79
Titov et al. 76
Uchida et al. 85
Vosyliene 87
Whaley 75
Whitney and Pierce 57
Woodward and Strange 87
Wydoski and Wedemeyer 76
Zalewski et al. 75

Both Behavior and Physiology:

Also see "Behavior (only)" or "Physiology (only)" and "General" above; articles listed under "Undetermined" below might also be pertinent.

Balayev 81
Bary 56
Biswas 71
Biswas and Karmarkar 76
Blancheteau et al. 61
Cowx 90b
Curry 75
Daniulyte and Malukina 69
Ellis 75
Ellis 75b
Emery 84
Halsband 59
Halsband 67
Harris 53
Haskell and Adelman 55
Holmes et al. 90
Horak 63
Johnson et al. 56
Klima 72
Kolz and Reynolds 89
Kuhn et al. 55
Kuroki 69
Kynard and Lonsdale 75
Lagler 78
Lamarque 63
Lamarque 67a
Lamarque 79b
Lamarque 90a
Le Men 80a
Le Men 80b
Lelek 66
Loeb 55
Maciolek and Timnol 80
McCarthy 90
McLain and Nielsen 53
McSwain 88
Mel'nikov and Prel' 82
Mesa 89
Mesa and Schreck 89
Mitra and Biswas 69b
Miyake and Steiger 57
Nakatani 54
Northrop 62
Northrop 67
Omand 50
Penáz and Prokes 73
Petrauskiene 87
Regis et al. 81
Scheminzky 24
Smith 74
Spiecker 57
Van Harreveld 38
Vibert 63
Vincent 71
Wolf 76
Wydoski 80
Zonov 75
Zonov and Spodobina 80

Injury and Mortality

Non-fatal Injury (only):

Covers physical damage to fish not resulting in immediate or near-term mortality. Also see "Both Non-Fatal Injuries and Mortality" below and "General" above; articles listed under "Undetermined" below might also be pertinent.

Hartley 67b
Kynard and Lonsdale 75
McCrimmon and Bidgood 65
Meyer and Miller 91
Northrop 67
Reynolds et al. 88
Smith 78
Thompson 60
Vincent 71
Volf 53

Mortality (only):

Also see "Both Non-fatal Injury and Mortality" below and "General" above; articles listed under "Undetermined" below might also be pertinent.

Barrett and Grossman 88
Bouck and Ball 66
Chmielewski et al. 73a
Collins et al. 54
Cumming et al. 75
Dahl and McDonald 80
Ellis 74
Eloranta 90
Fletcher 87
Godfrey 57
Horak and Klein 67
Kirkland 62
Kuroki 69
Lagler 78
Lamarque 67b
Levesque 71
Loeb 55
Maciolek and Timnol 80
Mann 75
Maxfield et al. 71
McLain 57
Mesa 89
Pugh 62
Rollefson 58a
Rollefson 58b
Sharber and Hudy 86
Spencer 66
Tolpygo and Parfenova 86
Whaley 75
Whaley and Maughan 75
Whaley et al. 78
Wiley and Tsai 83
Willemsen 90
Wydoski 80
Zonov and Spodobina 80

Both Non-fatal Injury and Mortality:

Also see Non-fatal Injury (only)" or Mortality (only)" and "General" above; articles listed under "Undetermined" below might also be pertinent.

Cowx 90b
Emery 84
Hale et al. 84
Hauck 49
Holmes et al. 90
Horak 63
Hudy 84
Hudy 85
Lamarque 90a
Lamarque 90b
McMichael et al. 91
Morgan 53
Nehring 91
Orsi and Short 87
Patten and Gillaspie 66
Petty 55
Pratt 55
Rauck 80
Seehorn 68
Sharber and Carothers 88
Sharber and Carothers 90
Shentyakova et al. 70
Shetter et al. 69
Smith and Elson 50
Spencer 67
Taylor et al. 57

Reproduction and Early Life Stages:

Covers reproductive behavior and physiology, gametes, embryos, larvae, and young-of-the-year juveniles. Also see "General" above; articles listed under "Undetermined" below might also be pertinent.

Biswas and Karmarkar 76
Dwyer 91
Collins et al. 54
Copp 89a
Copp 90
Copp and Penaz 88
Cowx 90b
Dodge 65
Elder 54
Flux 67
Fouberg 78
Godfrey 57
Horak 63
Khakimullin and Parfenova 84
Kmiotek and Helm 61
Lamarque 90a
Luczynski and Kolman 87
Maiselis and Shabanov 75
Marriott 73
Maxfield et al. 71
Morris and Novak 68
Petty 55
Pugh 62
Riedel 52
Scheminzky 22
Shentyakova et al. 70
Zonov and Spodobina 80

Undetermined:

Covers unseen literature which by title or other information is believed to include information on the effects of electrical fields on fish, but for which more specific categories could not be assumed.

FACTORS AFFECTING FISH RESPONSE AND ELECTROFISHING EFFICIENCY

Equipment and Techniques:

Covers electrical parameters (e.g., voltage, current, AC, DC, pulse frequency, and duration, waveform) and aspects of equipment and its use that affect those parameters (e.g., electrode shape, size, and position). Also see "General" above and "General: Equipment, Biological, and Physical" below.

Hudy 84
Jackson 55
James et al. 87
Johnson et al. 90
Kennedy 81
Kirkland 62
Klima 72
Kolz 89a
Kreutzer 64
Lagler 78
Lamarque 75b
Lamarque 77a
Lamarque 79b
Lamarque and Gosset 75b
Larimore et al. 50
Larson et al. 86
Layher and Maughan 83
Le Cren 74
Lelek 66
Lennon and Parker 57
Levesque 71
Lui et al. 90
Maiselis 56
Maksimov 77
Malkevicius and Toliusis 87
Martinez and Tiffan 89
Maxfield et al. 69
McCarthy 90
McGrath 65
McLain 57
McLain et al. 65
McSwain 88
Meyer and Miller 91
Miller 62
Mishelovich 74
Mishelovich 78
Monan and Engstrom 63
Moore 68
Muira et al. 72
Nakatani 55
Nelson and Little 87
Niemuth and Klingbiel 62
Northrop 62
Novotny 90
Nowak and Walus 64
Oren and Fried 59
Parrish et al. 85
Peduzzi and Meng 76b
Penczak and Romero 90
Persat and Copp 90
Philippart 79
Phillips 70b
Pierce et al. 85

Hudy 85
Jacobs and Swink 82
Jesien and Hocutt 90
Joswiak et al. 80
Kennedy and Strange 78
Klein 67
Klima 74
Kolz and Reynolds 89
Kuhn et al. 55
Lamarque 63
Lamarque 76a
Lamarque 77b
Lamarque 83
Lamarque et al. 78
Larkin 50
Latta and Myers 61
Layher and Maughan 84
Le Men 79
Lennon 59
Lennon and Parker 58
Lippet 78
Maciolek and Timnol 80
Maiselis and Mishelovich 75a
Maksimov et al. 87
Mann 75
Maxfield and Garrett 58
Maxfield et al. 70
McCrimmon and Berst 63
McGrath et al. 69
McLain and Dahl 68
McMichael et al. 91
Mesa 89
Meyers 51
Ming 64a
Mishelovich 75b
Mishelovich and Ivliev 83
Monan et al. 67
Morgan 53
Muncy 58
Namboodiri et al. 77
Newburg 73
Nikonorov 64
Northrop 67
Novotny and Priegel 71
Nusenbaum et al. 68
Orsi and Short 87
Patriarche and Gowing 66
Peduzzi and Meng 76c
Penczak and Zalewski 73
Petel and Planquette 75
Phillips 69
Phillips and Scolaro 80
Pitkanen 55

Hume 84
Jahn 79
Johnson et al. 56
Karlstrom 76
Kennedy and Strange 81
Klein and Lukowicz 79
Koehn and McKenzie 85
Kolz and Reynolds 90
Kuroki 69
Lamarque 67a,b
Lamarque 76b
Lamarque 79a
Lamarque 90a
Larimore 61
Larsen 55
Lawanyawudhi 82
Lazauski 84
Lee 80
Lennon 61
Lethlean 54
Loeb 58b
Madsen 73
Maiselis et al. 74
Malkevicius 87
Mann and Penczak 84
Maxfield et al. 59
McCann 66
McCrimmon and Bidgood 65
McKenzie and Pring 88
McLain and Nielsen 53
McMillan 28
Mesa and Schreck 89
Micha et al. 75
Miranda et al. 87
Mishelovich 75c
Mishelovich and Spodobina 78
Moore 54
Morris 50
Murray 58
Nelson and Little 86
Newman 59
Noble 70
Novotny 69
Novotny and Priegel 74
Omand 50
Ovsyankin 75
Peduzzi and Meng 76a
Penáz and Prokes 73
Penczak and Zalewski 81
Petty 55
Phillips 70a
Pickard et al. 83
Pratt 52

Pratt 55
Protasov et al. 82
Pygott et al. 90
Rawstron (no date)
Rees 78
Riedel 52
Ruhr 57
Scarnecchia 80
Seawell and Hevel 78
Seidel and Klima 74
Shabanov 75
Sharber and Carothers 90
Sharpe 64
Shentyakova et al. 70
Silver 57
Smith 74
Spiecker 57
Stewart 74b
Stewart 81
Strakhov 75
Strange et al. 89
Szatybelko 79
Thompson 59
Titov et al. 76
Uchida et al. 85
Vincent 71
Walker and Beach 79
Weiss and Cross 74
Whaley 75
Wiley and Tsai 83
Woest 77
Woodrum 78a
Zalewski 82
Zalewski and Cowx 90
Zhong 90
Zook 80
Priegel and Novotny 75
Pugh 62
Rask 74
Rawstron 78
Reynolds and Simpson 78
Riggs 55
Sanderson 60
Scheminzky 24
Sedgwick 78
Seidel and Watson 78
Sharber and Carothers 87
Sharber and Hudy 86
Sharpe and Burkhard 69
Shetter et al. 69
Simonaviciene 87a
Smith et al. 58
Stewart (no date)
Stewart 75a
Stewart 90a
Strakhov and Mishelovich 68
Stubbs 66
Taft 86
Thompson 60
Tolpygo and Parfenova 86
Van Harreveld 38
Volf 53
Wawrowski 84
Weisser and Klar 90
Whaley and Maughan 75
Willemsen 90
Wolf 76
Wydoski and Wedemeyer 76
Zalewski 83
Zalewski et al. 75
Zonov 74
Primmer 74
Pyatnitskiy and Stepanova 86
Rauck 80
Raymond 56
Reynolds et al. 88
Rollefson and Tanner 61
Saunders and Smith 54
Scheminzky 36
Seehorn 68
Serns 83
Sharber and Carothers 88
Sharkey 71
Shaurin et al. 75
Shilenko 80
Simpson 78
Smith et al. 59
Stewart 67
Stewart 79
Stewart 90b
Strakhov and Nusenbaum 59
Swingle et al. 66
Tester 52
Timmons 75
Trofimova 84
Viaud and Dreyfus 57
Von Geldern 71
Weber 73
Welton et al. 90
Whaley et al. 78
Williams 84
Woodbury 46
Young 75
Zalewski 85
Zalewski et al. 88
Zonov et al. 78

Biological:

Covers biological parameters such as species, size, shape and condition. Also see "General" above and "General: Equipment, Biological, and Physical" below.

Adams et al. 72
Balayev and Fursa 80
Bird and Cowx 90
Copp 89a
Cowx et al. 90
Ebbers 87
Ellis and Pickering 73
Flux 67
Funk 57b
Hartley 90a
Koehn and McKenzie 85
Kolz and Reynolds 90
Lamarque 67a
Bain et al. 85
Barham et al. 87
Boxrucker and Ploskey 88
Corcoran 79
Cross and Stott 75
Edwards and Higgins 73
Favro et al. 86
Forney 61
Funk 58
Iwaszkiewicz 64
Kolz 89a
Kuroki 69
Lamarque 79b
Balayev 81
Bary 56
Chmielewski et al. 73a
Courtney and Hensley 80
Daniulyte and Pyatrauskene 87
Ellis 72
Fisher and Elson 50
Fouberg 78
Godfrey 56
Junge and Libosvarsky 65
Kolz and Reynolds 89
Lagler 78
Lamarque 90a

Larson et al. 86
Lewis and Charles 58
Libosvarsky 90
Lukashov and Usachev 63
Maiselis and Mishelovich 75a
Maksimov et al. 87
McClendon and Rabeni 86
McSwain 88
Neate 68
Noble 70
Oren and Fried 59
Peduzzi and Meng 76b
Philippart 79
Pratt 55
Rauck 80
Seawell and Hevel 78
Shabanov 75
Smith 74
Stewart 79
Stewart 90b
Taft 86
Vibert 63
Whaley and Maughan 75
Yundt 83b
Zalewski and Cowx 90
Lelek 62
Libosvarsky 66a
Libosvarsky and Lelek 65
Maciolek and Timnol 80
Maiselis et al. 74
Malvestuto and Sonski 90
McLain and Dahl 68
Monan and Engstrom 63
Nelson and Little 86
Northrop 62
Ovsyankin 75
Penczak and Romero 90
Phillips and Scolaro 80
Pugh et al. 71
Saksgard and Heggberget 90
Seidel and Klima 74
Simonaviciene 87a
Smith et al. 59
Stewart 81
Sullivan 56
Taylor et al. 57
Welton et al. 90
Wiley and Tsai 83
Zalewski 83
Lelek 66
Libosvarsky 67b
Loeb 58a
Mahon 80
Maksimov 77
McCarthy 90
McLain et al. 65
Nakatani 54
Nikonorov 64
Nusenbaum et al. 68
Parrish et al. 85
Penczak and Zalewski 81
Pratt 52
Rask 74
Sanderson 60
Serns 83
Simpson 78
Stewart 75a
Stewart 90a
Szatybelko 79
Timmons 75
Whaley 75
Yundt 83a
Zalewski 85

Physical:

Covers environmental or habitat parameters such as water conductivity and temperature, and shape and size of the channel or basin that confines the field. Also see "General" above and "General: Equipment, Biological, and Physical" below.

Barham et al. 88a
Cuinat 67
DeMont 71
Gerdeaux and Jestin 78
Horak 63
Lamarque 77a
Lennon and Parker 58
Maiselis and Mishelovich 75b
Martinez and Tiffan 89
McClendon and Rabeni 86
Mitra and Biswas 69a
Peduzzi and Meng 76c
Pierce et al. 85
Ruhr 57
Shilenko 80
Thompson 60
Weber 73
Barham et al. 89b
De Groot and Boonstra 70
Fisher and Elson 50
Halsband 77
Jensen and Johnsen 88
Latta and Myers 61
Lewis and Charles 58
Malvestuto and Sonski 90
Maxfield et al. 69
Mishelovich 75c
Nehring 91
Penáz and Prokes 73
Pugh 62
Seehorn 68
Shilenko 83
Vincent 71
Zalewski 82
Bruschek 67
Dembinski and Korycka 74
Flux 67
Haskell 50
Kirkland 62
Lennon 59
Lewis et al. 62
Mann 75
McCauley 60
Mishelovich and Shilenko 78
Novotny and Priegel 71
Penczak 85
Pugh et al. 71
Sharber and Hudy 86
Tebo 65
Wawrowski 84

General: Equipment, Biological, and Physical:

Also see "General" above.

Anonymous 78c
Elson 50
Klein Breteler et al. 90
Clark 85
Hale et al. 84
Lamarque 90b
Eloranta 90
Halsband 67
Lamarque and Gosset 75a

Lamarque et al. 75
Le Men 80b
Loeb 57
Mishelovich and Aslanov 90
Paragamian 89
Penczak and Jakubowski 90
Quinn 86
Regis et al. 81
Rollefson 58b
Serns 82
Spencer 66
Welcomme 75
Wydoski 80
Larimore 57
Liu 90
Lorenz 84
Morris and Novak 68
Patten and Gillaspie 66
Peterman 78
Quinn 90
Reynolds 78
Saltveit 90
Smith 78
Von Geldern 62
Whitney and Pierce 57
Zalewski 86
Le Men 80a
Loeb 55
Mel'nikov and Prel' 82
Namboodiri and Verghese 69
Penczak 67
Purkett 57
Randall 90
Rollefson 58a
Serafy et al. 88
Smith and Elson 50
Webster et al. 55
Witt and Campbell 59

COMPARISONS OF EFFECTS OR FACTORS WITH NON-ELECTRIC GEAR OR TECHNIQUES:

Mostly comparisons of relative efficiencies in specific situations. Also see "General" above.

Bain 88
Boccardy and Cooper 63
Bozek and Rahel 91
Cadwallader 84
Cumming et al. 75
Dauble and Gray 80
Fisher 87
Fouberg 78
Germann and Sandow 76
Hall and Durham 79
Hickley and Starkie 85
Holmes et al. 90
Jacobs and Swink 82
Klein Breteler et al. 90
Layher and Maughan 83
Lorenz 84
Micha et al. 75
Nelson and Little 86
Parrish et al. 85
Purkett 57
Regis et al. 81
Ruhr 57
Serafy et al. 88
Stewart (no date)
Thompson 60
Welcomme 75
Woodrum 78a
Barry 67
Bouck and Ball 66
Brenner and Noble 82
Clark 85
Cunjak et al. 88
Ebbers 87
Fletcher 87
Funk 57b
Griffith 81
Harris et al. 79
Hickman and Hevel 75
Horak and Klein 67
Kennedy and Strange 81
Larimore 57
Layher and Maughan 84
Mann 75
Miranda et al. 87
Newburg 73
Polovino et al. 82
Pygott et al. 90
Reynolds and Simpson 78
Sanderson 60
Smith and Elson 50
Swingle et al. 66
Timmons 75
Wiley and Tsai 83
Zalewski and Penczak 81
Bennett and Brown 68
Boxrucker and Ploskey 88
Buynak et al. 89
Cowx et al. 90
Dahl and McDonald 80
Favro et al. 86
Forney 61
Funk 58
Guest 84
Harrison 57
Hockin et al. 85
Jackson 85
Klein and Lukowicz 79
Larson et al. 86
Loeb 58a
McClendon and Rabeni 86
Namboodiri et al. 77
Noble 70
Primmer 74
Rees 78
Riel 66
Seawell and Hevel 78
Stevenson and Day 86
Taft 86
Von Geldern 62
Willemsen 90

TAXA FOR EFFECTS ON FISH OR FACTORS AFFECTING FISH RESPONSE

By species for selected families of fishes represented in the Colorado River System, families in systematic order; by family for others, in alphabetical order. This index is intended for cross reference with categories on effects and factors above.

Cyprinidae by Species

Cyprinids in North America

Campostoma anomalum: Larimore 57
Campostoma oligolepis: Barrett and Grossman 88

Carassius auratus:
Kolz and Reynolds 89
Lui et al. 90
Simonaviciene 87b
Clinostomus funduloides:
Ctenopharyngodon idella:
Cyprinus carpio:
Loeb 55
Lui et al. 90
Rollefson 58b
Zhong 90
Hypophthalmichthys molitrix:
Hypophthalmichthys nobilis:
Leuciscus idus:
Luxilus coccogenis:
Luxilus cornutus:
Notemigonus crysoleucas:
Notropis species:
Notropis whipplei:
Notropis leuciodus:
Pimephales notatus:
Ptychocheilus oregonensis:
Maxfield et al. 69
Rhinichthys cataractae:
Rhinichthys atratulus:
Rhodeus sericeus:
Semotilus atromaculatus:
Tinca tinca:

Other Cyprinids
Abramis ballerus:
Abramis brama:
Lukashov and Usachev 63
Abramis species:
Blicca björkna:
Carassius vulgaris [?]:
Catla catla:
Cirrhinus mrigala:
Leuciscus cephalus:
Penáz and Prokes 73
Leuciscus leuciscus:
Megalobrama amblycephala:
Phoxinus laevis:
Rutilus rutilus:
Mann 75
Rutilus species:

Catostomidae by Species
Catostomus ardens:
Catostomus catostomus:
Catostomus commersoni:
Erimyzon oblongus:
Hypentelium nigricans:

Joswiak et al. 80
Kolz and Reynolds 90
Northrop 62
Van Harreveld 38
Barrett and Grossman 88
Cumming et al. 75
Barham et al. 89a
Loeb 57
Maciolek and Timnol 80
Taylor et al. 57
Zonov and Spodobina 80
Liu 90
Liu 90
Halsband 59
Barrett and Grossman 88
Adams et al. 72
Lewis and Charles 58
Barrett and Grossman 88
Lewis and Charles 58
Barrett and Grossman 88
Larimore 57
Maxfield and Garrett 58
Maxfield et al. 70
Barrett and Grossman 88
Godfrey 56
Zalewski et al. 75
Barrett and Grossman 88
Halsband 59

Shentyakova et al. 70
Shentyakova et al. 70

Willemsen 90
Halsband 59
Viaud and Dreyfus 57
Mitra and Biswas 69b
Mitra and Biswas 69b
Lelek 66

Mann 75
Zhong 90
Halsband 59
Copp 90
Shabanov 75
Willemsen 90

Taylor et al 57
McLain 57
Lewis and Charles 58
Lewis and Charles 58
Barrett and Grossman 88

Kolz 89b
Lewis and Charles 58
Scholz 83
Wolf 76

Zhong 90
Halsband 59
Loeb 58a
Rollefson 58a
Whitney and Pierce 57

Zhong 90
Zhong 90

Larimore 57

Maxfield et al. 59

McLain 57
Regis et al. 81

Mel'nikov and Prel' 82

Libosvarsky 67b

Lukashov and Usachev 63
Shentyakova et al 70

McLain and Nielsen 53

***Minytrema melanops*:** Germann and Sandow 76

Ictaluridae by Species

***Ameiurus brunneus*:** Corcoran 79

***Ameiurus catus*:** Corcoran 79; Hale et al. 84; Nelson and Little 86

***Ameiurus melas*:** McLain and Nielsen 53; Morris and Novak 68; Regis et al. 81

***Ameiurus natalis*:** Corcoran 79; Lewis and Charles 58; Nelson and Little 86

***Ameiurus nebulosus*:** Hale et al. 84; McLain 57; Morris and Novak 68; Nelson and Little 86; Regis et al. 81; Zalewski et al. 75

***Ameiurus platycephalus*:** Corcoran 79

***Ameiurus species*:** Larimore 57

***Ictalurus furcatus*:** Corcoran 79; McSwain 88; Morris and Novak 68; Nelson and Little 86

***Ictalurus punctatus*:** Corcoran 79; Curry 75; Curry and Kynard 78; Edwards and Higgins 73; Ellis 74; Ellis 75a; Ellis 75b; Hale et al. 84; Jesien and Hocutt 90; Morris and Novak 68; Nelson and Little 86; Spencer 67; Taylor et al. 57

***Ictalurus species*:** Curry 75; Curry and Kynard 78; Nelson and Little 86

***Noturus gyrinus*:** Corcoran 79

***Noturus insignis*:** Corcoran 79

***Pylodictis olivaris*:** Corcoran 79; Nelson and Little 86; Gilliland 87; McSwain 88; Morris and Novak 68; Muncy 58; Quinn 86; Quinn 90

Unspecified Ictalurid Species: Hale et al. 84

Esocidae by Species

***Esox lucius*:** Holmes et al. 90; Klein Breteler et al. 90; Kmiotek and Helm 61; Mann 75; McLain and Nielsen 53; Shetter 38

Salmonidae by Species

***Coregonus albula*:** Luczynski and Kolman 87

***Coregonus lavaretus*:** Luczynski and Kolman 87

***Coregonus peled*:** Maiselis and Mishelovich 75b; Zonov and Spodobina 80

***Coregonus pidschian*:** Holmes et al. 90

***Coregonus sardinella*:** Holmes et al. 90

***Prosopium williamsoni*:** Taylor et al. 57

***Oncorhynchus clarki*:** Bozek and Rahel 91; Mesa 89; Dwyer 91; Mesa and Schreck 89; Morris 50

***Oncoryhnchus gorbuscha*:** Marriott 73

***Oncorhynchus keta*:** Maiselis and Shabanov 75

***Oncorhynchus kisutch*:** Johnson et al. 56; Nakatani 54; Nakatani 55; Neate 68; Orsi and Short 87; Pugh 62; Pugh et al. 71; Raymond 56

***Oncorhynchus mykiss*:** Dwyer 91; Hauck 49; Holmes et al. 90; Hudy 85; Lennon 59; Maxfield et al. 71; McCrimmon and Bidgood 65; McLain 57

McLain and Nielsen 53	McMichael et al. 91	Nakatani 54
Nehring 91	Pratt 55	Pugh et al. 71
Reynolds et al. 88	Rollefson 58a	Rollefson 58b
Sharber and Carothers 88	Sharber and Carothers 90	Shetter et al. 69
Taylor et al. 57	Vibert 63	Vosyliene 87
Whaley 75	Yundt 83b	
***Oncorhynchus nerka*:**	Monan and Engstrom 63	Nakatani 54
Thompson 60		
***Oncorhynchus tshawytscha*:**	Nakatani 54	Orsi and Short 87
Pugh et al. 71		
Salmo lacustris [?]:	Scheminzky 22	
***Salmo salar*:**	Amiro 90a	Amiro 90b
Fisher and Elson 50	Godfrey 56	Godfrey 57
Hartley 90a	Jensen and Johnsen 88	Lennon 59
Murray 58	Randall 90	Saksgard and Heggberget 90
Saltveit 90	Stewart 67	Stewart 81
Stewart 90b	Strange et al. 89	
***Salmo trutta*:**	Favro et al. 86	Flux 67
Gatz et al. 86	Halsband 59	Jensen and Johnsen 88
Koehn and McKenzie 85	Lamarque 67a	Lamargue 67b
Lamarque 90	Larsen 55	Nehring 91
Northrop 62	Pratt 55	Rollefson 58a
Rollefson 58b	Saltveit 90	Shetter 38
Stewart 67	Strange et al. 89	Vibert 63
Yundt 83a	Yundt 83b	
***Salmo* species, unspecified:**	Bijlard 82	Bouck and Ball 66
Bouck et al. 78	Chmielewski et al. 73a	Curry 75
Curry and Kynard 78	Horak and Klein 67	Kynard and Lonsdale 75
Madden and Houston 76	Monan et al. 67	Reynolds et al. 88
Schreck et al. 76	Sharber and Carothers 88	Sharber and Carothers 90
Sloley et al. 86	Uchida et al. 85	Woodward and Strange 87
Zonov and Spodobina 80		
***Salvelinus fontinalis*:**	Godfrey 56	Godfrey 57
Hudy 84	Hudy 85	Kuroki 69
Lennon 59	McLain and Nielsen 53	Murray 58
Pratt 55		
***Thymallus arcticus*:**	Holmes et al. 90	
***Thymallus thymallus*:**	Regis et al. 81	
Unspecified salmonid species:	Bohlin 84	Burrows 57
Carr 68	Collins et al. 54	Gunstrom and Bethers 85
Harris 53	Karlstrom 76	Kennedy 81
Meyer and Miller 91	Mishelovich 75c	Mishelovich and Spodobina 78
Muraveiko 80	Newman 59	Shabanov 75Volf 53

Percichthyidae by Species

***Morone saxatilis*:**	Rees 78	
***Dicentrarchus labrax*:**	Le Men 80a	Le Men 80b

Centrarchidae by Species

***Ambloplites rupestris*:**	McClendon and Rabeni 86	
***Lepomis cyanellus*:**	Gatz and Adams 87	Lewis and Charles 58
***Lepomis gibbosus*:**	McLain 57	Northrop 62
***Lepomis macrochirus*:**	Edwards and Higgins 73	Gatz and Adams 87

Percidae by Species

Cottidae by Species

Others by Family

Cichlidae:
Barham et al. 88a
Biswas and Karmarkar 76
Namboodiri 66
Clariidae:
Namboodiri and Verghese 69
Clupeidae:
Kazlauskiene 87
Klima 74
Levesque 71
Stepanova 82
Cobitidae:
Echeneidae:
Electrophoridae:
Eleotridae:
Elopidae:
Engraulidae:
Gadidae:
Harris 53
Le Men 80a
Shparkovsky and Vataev 85
Stewart 90b
Gasterosteidae:
Gobiidae:
Kuhliidae:
Morgan 53
Labridae:
Mugilidae:
Maciolek and Timnol 80
Osmeridae:
Willemsen 90
Petromyzontidae:
Dodge 65
McLain 57
Weisser and Klar 90
Pimelodidae:
Pleuronectidae:
Kazlauskiene and Daniulyte 87
Stewart 90b
Poeciliidae:
Sciaenidae:
Scomberesocidae:
Scombridae:
Klima 74
Siluridae:
Soleidae:
Sparidae:
Stromateidae:
Synbranchidae:
Trichomycteridae:
Zoarcidae:

Barham and Schoonbee 90
Barham et al. 88b
Courtney and Hensley 80
Namboodiri and Verghese 69
Courtney and Hensley 80
Oren and Fried 59
Halsband 59
Kazlauskiene and Daniulyte 87
Le Men 80a
Maksimov 77

Maciolek and Timnol 80
Klima 72
Lamarque 79b
Maciolek and Timnol 80
Namboodiri 66
Klima 72
Godfrey 56
Kazlauskiene 87
Le Men 80b
Stewart 79

Halsband 59
Maciolek and Timnol 80
Maciolek and Timnol 80
Tester 52
Stewart 81
Le Men 80a

Halsband 59

Applegate et al. 52
Godfrey 56
McLain and Dahl 68

Corcoran 79
Halsband 59
Stewart 79

Maciolek and Timnol 80
Klima 72
Nikonorov 64
Halsband 59
Maksimov 77
Halsband 59
De Groot and Boonstra 70
Klima 72
Klima 72
Maciolek and Timnol 80
Corcoran 79
Halsband 59

Barham et al. 87
Barham et al. 89b
Maciolek and Timnol 80

Namboodiri 66

Harris 53
Klima 72
Le Men 80b
Seidel and Klima 74

Halsband 59
Kazlauskiene and Daniulyte 87
Shentyakova et al. 70
Stewart 81

Zalewski et al. 75
Miyake and Steiger 57

Stewart 90b
Le Men 80b

McLain 57

Dahl and McDonald 80
McCauley 60
McLain et al. 65

Kazlauskiene 87
Stewart 81

Klima 74

Klima 72
Miyake and Steiger 57

Horn 77
Klima 74

GEAR DESIGN, CONSTRUCTION, AND OPERATION

Boats or Raft Mounted Gear:

Covers gear in which electrofishing apparatus and personnel are intended to operate from the vessel; usually used in deeper streams and lentic waters. Also see "General" above and "Universal, General or Undetermined" below for articles on electrical components potentially used with many types of gear or general coverage of most categories of electrical fishing or guidance gear. Some entries under "Combined With or Electrical Modifications of Other Gear" (e.g., electric trawls and some electric seines) also are mounted on or used with boats.

Wading (Portable) Gear:

Covers backpack, towed, or shore-based gear with which electrodes are usually deployed and fish retrieve by wading; usually used along shores or in shallow streams and ponds. Also see "General" above and "Universal, General or Undetermined" below for articles on electrical components potentially used with many types of gear or general coverage of most categories of electrical fishing or guidance gear. Some entries under "Combined With or Electrical Modifications of Other Gear" (e.g., some electric seines) also are used while wading.

Screens (barriers) or Guidance Systems:

Also see "General" above and "Universal, General or Undetermined" below for articles on electrical components potentially used with many types of gear or general coverage of most categories of electrical fishing or guidance gear.

Combined With or Electrical Modifications of Other Gear:

Also see "General" above and "Universal, General or Undetermined" below for articles on electrical components potentially used with many types of gear or general coverage of most categories of electrical fishing or guidance gear.

Universal, General or Undetermined:

Covers articles concerning equipment used by most types of electrical fishing gear (e.g., pulse and waveform generators or controls); general reviews of most types of electrical fishing gear, and unseen literature which by title or other information for which more specific categories could not be assumed based on titles or other available information. Also see "General" above.

Burnet 53
Cadwallader 84
Cattley 55b
Chmielewski 90
Cowx 90b
Dembinski & Chmielewski 71a
Dickson 54
Ducharme 69
Ellis and Hoopes 72
Funk 57a
Goodchild 90
Gosset 76
Grunwald 83
Hanson 63
Hartley 67b
Hartley and Weiss 75a
Haskell 50
Hickley 82
Holton and Sullivan 54
Jackson 55
Joswiak et al. 80
Koehn and McKenzie 85
Kuderskij and Zonov 78
Lagler 78
Lamarque 76b
Lamarque 79a
Lamarque and Gosset 75a
Lamarque et al. 78
Lazauski 84
Le Men 80a
Lennon 61
Lippet 78
Mann and Penczak 84
McGrath et al. 69
McSwain 88
Mishelovich 75c
Moore 54
Nelva et al. 79
Novotny 90
O'Connell 56
Patriarche and Gowing 66
Penczak 67
Phillips and Scolaro 80
Rayner 50
Rollefson and Tanner 61
Sharber and Carothers 87
Silver 57
Stewart 74b
Thomas 63
Tweddle et al. 79
Walker and Beach 79
Weiss 72
Weiss and Cross 74
Burnet 61
Carr 68
Chambers 84
Cochran 63
Cui 83
Dethloff 59
Dodson 61
Egov and Genikhov 87
Elson 50
Gilliland 87
Gosset 74
Gosset et al. 71
Hale et al. 84
Hartley 65
Hartley 75
Hartley et al. 67
Haskell 54
Hickley 85
Hosl 59b
Jahn 79
Kedzior and Penczak 72
Kreutzer 64
Kuroki 59
Lamarque 75a
Lamarque 77a
Lamarque 83
Lamarque and Gosset 75b
Larkin 50
Lazauski and Malvestuto 84
Le Men 80b
Lennon and Parker 57
Maiselis 56
McCann 66
McKenzie and Pring 88
Miller 62
Mishelovich 78
Morris and Novak 68
Northrop 62
Nowak and Walus 64
Omand 50
Peduzzi and Meng 76a
Petel and Planquette 75
Pitkänen 55
Rollefson 58a
Seidel and Klima 74
Sharkey 71
Smith et al. 73
Stewart 75a
Thompson 60
Von Brandt 85
Wawrowski 84
Weiss 75
Weisser and Klar 90
Burnet 67
Cattley 55a
Chmielewski 81
Coles et al. 85
Cuinat 63
Dethloff 64
Dow 80
Ellis 71
Funk 49
Goodchild 86
Gosset 75
Grudtsin and Ponuklain 75
Halsband 73
Hartley 67a
Hartley 80b
Haskell 40a
Haskell and Zilliox 41
Hofstede 67
Hume 84
Jones 59
Knight 78
Kristjonsson 59
Kuroki 69
Lamarque 75b
Lamarque 77b
Lamarque 90b
Lamarque et al. 75
Lawanyawudhi 82
Le Men 79
Lennon 59
Levesque 71
Malkevicius and Malkevicius 87
McGrath 65
McLain et al. 65
Mishelovich 75b
Mishelovich and Ivliev 83
Murray 58
Novotny 69
Nusenbaum et al. 68
Orsi and Short 87
Peduzzi and Meng 76c
Philippart 79
Priegel and Novotny 75
Rollefson 58b
Senn et al. 84
Shaurin et al. 75
Steinmetz 90
Strakhov and Nusenbaum 59
Trofimova 84
Von Geldern 62
Weber 73
Weiss 76
Welcomme 75

Williams 84
Woest 77
Woodrum 78b
Zalewski 82

APPLICATIONS, SAMPLING DESIGN, AND ANALYSIS

Applications and (or) Sampling Design (only):

Also see "General" above and "Both Applications (and/or Sampling Design) and Analysis below.

Aggus et al. 80
Amiro 90a
Anonymous 59
Anonymous 78b
Aslanov 82
Aslanov et al. 80
Backiel and Welcomme 80
Bagenal 78
Baggs, 1863
Bain 88
Bell 86
Belus 84
Benech 78
Bentz 53
Boccardy and Cooper 63
Brenner and Noble 82
Cameron and Gray 79
Carline et al. 84
Cattley 55a
Cattley 55b
Chaput and Claytor 89
Cochran 63
Coles et al. 85
Copp 90
Copp and Penaz 88
Cowx 90b
Dauble and Gray 80
Elsen et al. 86
Elson 50
Favro et al. 86
Frankenberger 60
Freytag and Horn 75
Funk 49
Funk 57b
Gardiner 84
Germann and Sandow 76
Giguère 54
Godfrey 56
Grivat 83
Gumerov 75
Hale et al. 84
Hall and Durham 79
Halsband 71a
Halsband 74
Halsband 77
Hankin 84
Harrison 57
Hartley 65
Hartley 67a
Hartley 80a
Hartley 90b
Hartley and Simpson 67
Hartley and Weiss 75a
Hartley and Weiss 75b
Heggberget and Hesthagen 79
Hendricks et al. 80
Hickley 86
Hickley 90
Hickley and Starkie 85
Hockin et al. 85
Hocutt and Stauffer 80
Hofstede 67
Holton and Sullivan 54
Hosl 59b
Iwaszkiewicz 64
Jackson 55
Jackson 85
Kedzior and Penczak 72
Kirkland 62
Klein and Lukowicz 79
Kreutzer 64
Kuderskij and Zonov 78
Kuroki 59
Lagler 78
Lamarque 67b
Lamarque 75a
Lamarque 75b
Lamarque 76a
Lamarque 76b
Lamarque 77a
Lamarque 79a
Lamarque 83
Lamarque 90b
Lamarque and Gosset 75a
Lamarque et al. 75
Larimore 61
Larkin 50
Larson et al. 86
Lawanyawudhi 82
Layher and Maughan 83
Layher and Maughan 84
Le Cren 74
Le Men 79
Le Men 80a
Le Men 80b
Lee 80
Lelek 62
Levesque 71
Lippet 78
Liu 90
Loeb 55
Loeb 58a
Lui et al. 90
Maciolek and Timnol 80
Madsen 73
Maiselis 56
Maiselis et al. 74
Mann 75
Mann 85
Mann and Penczak 84
Mathur and Heisey 80
Maxfield and Garrett 58
Maxfield et al. 69
McCann 66
McCarthy 90
McGrath et al. 69
McLain 57
McLain and Nielsen 53
McMillan 28
Mesa 89
Mesa and Schreck 89
Micha et al. 75
Miller 62
Moore et al. 86
Newburg 73
Nikonorov 64
Northrop 67
Novotny and Priegel 71
Nowak and Walus 64
Nusenbaum and et al 69
Omand 50
Ovsyankin 75
Pawaputanon 86
Penczak and Jakubowski 90
Petel and Planquette 75
Peterman 78
Philippart 79
Pickard et al 83
Pitkanen 55
Primmer 74
Purkett 57

Analysis (only):

Also see "General" above and "Both Applications (and/or Sampling Design) and Analysis below.

Both Applications (and/or Sampling Design) and Analysis:

Also see "General" and "Applications and (or) Sampling Design" or "Analysis above.

SAFETY, REGULATIONS, AND GUIDELINES:

Also see "General" above.

RELATED LITERATURE:

Non-Fish Aquatic Organisms:

Covers one or more of the above categories but with respect to non-fish organisms; those references included here and in above categories pertain to both fish and non-fish organisms. Also see "General" above.

Other

Publications not directly related to electrofishing but perhaps of interest or value; also some literature from the Burridge et al. (90) bibliography for which the title was insufficient to indicate direct reference to electrofishing

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APPENDIX II

Requests for Information and Surveys on Electrofishing

A. Photocopy of request for information on effects of electrofishing on fish published in *Fisheries* (16(3):52, May-June 1991). Similar requests were also printed and distributed in several other newsletters and bulletins.

B. Survey distributed to Colorado River Basin Researchers (upper and lower basins). A variation of the survey was also distributed to fishery biology faculty and graduate students at Colorado State University.

A. Photocopy of request for information on effects of electrofishing on fish published in *Fisheries* (16(3):52, May-June 1991). Similar requests were also printed and distributed in several other newsletters and bulletins.

Your Assistance is Requested Regarding the Effects of Electrofishing on Fish

Although electrofishing has long been documented to cause injury to fish under at least some operational and environmental conditions, many fishery biologists and managers consider the methodology, when properly used, to be relatively benign and effective. As such, it has been used extensively to collect and monitor endangered fishes in the Colorado River basin (e.g., Colorado squawfish, humpback chub, and razorback sucker). However, a recent investigation by Sharber and Carothers (*North American Journal of Fisheries Management* 8:117–122) using common electrofishing gear and techniques documented extensive, often overlooked injury to the vertebrae and adjacent tissues of adult rainbow trout collected in the Colorado River below Lake Powell. As a result of this and previous reports on injurious effects, many researchers and resource agencies are seriously concerned and reexamining their use of electrofishing for monitoring and studying endangered and other fishes.

Not all investigations conducted by the Larval Fish Laboratory at Colorado State University deal with the "little guys." We have been contracted by agencies associated with the lower Colorado River basin to review and evaluate existing information on electrofishing gear and techniques and their effects on fish. This spring and summer we intend to summarize that information, recommend measures or guidelines for minimizing or precluding detrimental effects, and suggest research to answer critical unresolved questions on the matter. Special emphasis will be placed on species and conditions most relevant to endangered species in mainstem rivers of the Colorado River basin. Similar or related studies are probably planned or underway elsewhere. If you are involved in any of these investigations we would like you to contact us to exchange information and avoid unnecessary replication of effort.

Some of you have extensive practical experience with electrofishing. To complement the published literature and make our survey and evaluation as comprehensive and up-to-date as possible, we request copies of your pertinent theses, reports, and unpublished manuscripts and data. We also solicit your personal observations, concerns, and suggestions on the matter, as well as information regarding recent (as yet unreported), current, or planned research or development regarding electrofishing effects, efficiency, gear, or techniques. We are especially interested in experiences with or attempts to refine or develop new electrofishing techniques or gear to minimize adverse effects (e.g., the new Coffelt CPS circuitry). Comparable information on the injurious effects of other, nonelectrical, collection techniques and gear is also needed. Inadvertent effects on fish eggs, larvae, early juveniles, and larger nontarget fishes are also of interest. We do not intend to "scoop" anyone's research or planned publications and will honor requests to keep information or sources confidential.

The recommendations resulting from this and perhaps similar investigations elsewhere may affect how you collect and monitor fish in the near future. We need your input as soon as possible. Please contact Darrel E. Snyder, Larval Fish Laboratory, Colorado State University, Fort Collins, Colorado 80523, 303/491-5295; Fax 303/491-5091.

APPENDIX II

B. Survey distributed to Colorado River Basin Researchers (upper and lower basins). A variation of the survey was also distributed to fishery biology faculty and graduate students at Colorado State University.

Colorado State University

Larval Fish Laboratory
Fort Collins, Colorado 80523
(303) 491-5295

To: Colorado River Basin Researchers
From: Darrel Snyder
Date: December 2, 1991

If you have personal electrofishing experience, and especially any with endangered species, please respond to this questionnaire within the next couple days and return it to me as soon as possible. Append responses on additional pages as necessary. No response or statement will be attributed personally to the respondent in my project report or any related publication without the respondent's specific permission.

SURVEY OF ELECTROFISHING EXPERIENCES, OBSERVATIONS AND RECOMMENDATIONS

PERSONAL DATA Name:
Agency or Firm:
Address:
Phone:

1. Please describe the nature and extent of your electrofishing experience? (supervisor, crew leader, crew member?)

2. What environments and under what environmental conditions have you sampled with electrofishing gear? (Rivers, streams, lakes or reservoirs; habitats; time of year, day or night, water temperatures, conductivities, other environmental conditions you consider important.)

3. What species and size groups have you sampled or monitored with electrofishing gear?

4. What electrofishing equipment and techniques have you used? (Type of gear, typical operational configuration and settings, special procedures or hints for optimum operation.)

5. Describe observations of adverse or injurious effects, especially with regard to endangered or related species. (Physical appearance, abnormal behavior, or mortalities to target fish, non-target fish (note species) or other aquatic organisms. Please note specific electrical field conditions or equipment configurations and settings under which these injuries were observed if you can remember or have access to that information. If you very rarely or have never observed electrofishing injuries, please say so.)

6 Based on your experience, what recommendations would you offer for optimal electrofishing efficiency while minimizing injury to fish? (Procedures, settings, dos and don'ts).

7 Please read the attached material abstracted from my report which is still in preparation. Please relate your response, thoughts, oversights, or criticisms on the content.

APPENDIX III

Threshold Values of Field Intensity for Characteristic Reactions
(Photocopy of Appendix 4 from Sternin et al. 1976, pages 272-283)

Threshold values of field intensity for characteristic reactions (photocopy of Appendix 4 from Stemin et al. 1976, pages 272-283). "I" is first reaction, reactive detection, or twitch; "II" is anodic taxis or forced swimming; "III" is stun, loss of equilibrium, narcosis, or tetany. For water conductivity, 1 mmho/m = 10 µS/cm; for current density, 10^{-6} A/mm² = µA/mm² = 100 µA/cm². No source references were given except in footnotes 6 and 7 where reference 142 is Shentyakov (1964), 174 is Halsband (1954), and 175 is Halsband (1955).

Direct current

Item No.	Fish	Size, cm	γ_w, mmho/m	Water temperature, °C	E_0, V/cm			$j_0 \cdot 10^{-6}$, A/mm²		
					I	II	III	I	II	III
1	2	3	4	5	6	7	8	9	10	11
1		6—8.7	—	—	—	—	—	0.18—0.14	1.3—0.9	1.8—1.3
2		9.5—9.7	—	—	—	0.53	0.82	—	—	—
3		60—64	—	—	—	—	—	0.18	1.26	1.82
4	Sculpin	65—69	—	—	—	—	—	0.18	1.28	1.70
5		70—74	—	—	—	—	—	0.18	1.18	1.50
6		75—80	—	—	—	—	—	0.17	1.08	1.44
7		87	—	—	—	—	—	0.14	0.89	1.34
8	Stone-loach	10—12	—	—	—	—	—	0.08	1.55	2.43
9		1.5—7.5	—	—	—	—	—	0.14—0.13	3.3—1.3	4.7—2.1
10		3.5—4.5	—	20	—	—	—	0.4	3.4	4—6
11		8—8.4	—	—	—	—	—	—	0.14	0.45
12	Minnow	15—20	—	—	—	—	—	0.19	3.30	4.74
13		21—30	—	—	—	—	—	0.18	3.13	4.74
14		31—40	—	—	—	—	—	0.13	2.32	3.94
15		51—60	—	—	—	—	—	0.11	1.42	2.50
16		61—75	—	—	—	—	—	0.13	1.28	2.15
17	Bitterling	4.4—4.5	9.4		0.266—0.298	1.23—1.48	2.44—2.53	0.25—0.28	1.15—1.39	2.29—2.56
18	Flounder	20—22	—		—	—	—	39.9	44.34	70.95
19		—	—	—	—	—	—	—	1.4	3.1—3.4
20	Crucian carp	4.5—4.9	9.4	—	0.309—0.382	1.3—1.69	2.28—2.49	0.29—0.36	1.22—1.68	2.14—2.34
21		6.5	—	—	—	—	—	—	0.48	0.69—0.99
22		6	33	15	—	—	0.3	—	—	0.99
23	Carp	1.3	9.4	—	—	—	—	0.58	1.9	2.6
24		5—8	—	—	—	—	—	—	—	3.2—3.36
25	Carp – crucian	6	33	15	—	—	0.42	—	—	1.38
26	carp (hybrid)	9—11	35	3—6	0.049—0.125	0.215—0.6	0.327—0.675	0.17—0.44	0.76—2.12	1.15—2.37
27	Carp – crucian carp (hybrid)	17—72	3.5	3—6	0.034—0.139	0.138—0.664	0.219—0.664	0.12—0.49	0.49—2.31	0.76—2.31
28	Muller	2.5—11	Sea water	—	—	—	—	1.2—2.87	7.0—20.4	—
29		3.0		—	—	—	—	28	125	—
30	Common Caspian kilka	7—12	The same	9—26	—	0.1—0.17	0.29—0.5	—	—	—
31	Stickleback	5—6	—	—	—	—	—	0.48	1.88	3.94
32		—	—	—	—	—	—	—	—	1.5
33	Perch	14.5	5.7	13	0.15	0.34	1.19	0.085	0.194	0.676
34		15	40	13	0.08	0.178	0.71	0.32	0.71	2.84
35		13.7	70	13	0.092	0.204	0.82	0.644	1.43	5.74
36		Small	—	—	—	—	—	0.2—0.5	—	2—5
37	Orfe	7.5	—	—	—	—	—	—	1.58	3.1—3.4
38	Roach	13	5.7	13	0.14	0.35	1.29	0.079	0.20	0.735
39		16	40	13	0.084	0.177	0.58	0.36	0.707	2.32
40		4.1	9.4	—	0.310	1.71	2.62	0.29	1.61	2.56
41	Baltic herring	15	51—74	15	0.033	0.084	0.416	—	—	—
42	Vimba	—	—	—	—	0.08—0.14	—	—	—	—
43			144‰		0.007—0.009	0.039—0.075	0.111—0.135	—	—	—
44	Jack mackerel	13—15.3	200‰	8—22	0.01—0.012	0.061—0.065	—	—	—	—
45			242‰		0.007—0.009	0.062—0.078	0.132—0.144	—	—	—
46		26	—	—	0.038	0.146	0.316	—	—	—
47	Cod	30	—	—	0 037	0.140	0.30	—	—	—
48		34	—	—	0.0353	0.135	5.285	—	—	—

Threshold values of field intensity for characteristic reactions (continued).

Item No.	Fish	Size, cm	γ_w, mmho/m	Water temperature, °C	E_0, V/cm			$j_0 \cdot 10^{-6}$, A/mm²		
					I	II	III	I	II	III
1	2	3	4	5	6	7	8	9	10	11
49		38	—	—	0.037	0.136	0.274	—	—	—
50		2.3	9.4	—	—	—	—	0.38	1.9	2.5
51		9.2—12	35	3—6	0.032—0.056	0.221—0.456	0.344—0.456	0.11—0.20	0.77—0.59	1.57—1.59
52		11	—	7	—	—	—	—	0.41	—
53	Trout	18.2—25.5	35	3—6	0.014—0.123	0.215—0.602	0.215—0.602	0.05—0.43	0.74—2.15	0.74—2.15
54			—	—	0.12	0.14—0.87	0.87—1.0	—	—	—
55			2	—	—	0.316—0.284	—	—	0.063	—
56			5	—	—	—	—	—	0.142	—
57		20	10	—	—	0.264	—	—	0.264	—
58			20	—	—	0.250	—	—	0.5	—
59			100	—	—	0.266	—	—	2.26	—
60			200	—	—	0.223	—	—	4.46	—
61			1000	—	—	0.202	—	—	20.2	—
62			4000	—	—	0.183	—	—	73	—
63		8.0—8.9			0.017—0.025	0.112—0.134	0.288—0.298	—	—	—
64	Anchovy (Azov)	9.0—9.9	16 — 18.5°/oo	8—22	0.016—0.024	0.109—0.125	0.291—0.315	—	—	—
65		12.0—12.9			0.018—0.032	0.071—0.083	0.173—0.22	—	—	—
66	Anchovy (Black Sea)	13.0—13.9	16—18.5°/oo	8—22	0.02—0.034	0.068—0.08	0.197—0.233	—	—	—
67		12.0—12.9			0.029—0.041	0.11—0.136	0.393—0.484	—	—	—
68		13.0—13.9			0.025—0.037	0.098—0.166	0.382—0.484	—	—	
69		26.4	5.7	13	0.112	0.25	0.99	0.064	0.142	0.565
70	Pike	26.7	40	13	0.071	0.154	0.62	0.284	0.615	2.48
71		29.5	70	13	0.065	0.14	0.56	0.455	0.98	3.92

Alternating current of industrial frequency

Item No.	Fish	Size, cm	γ_w, mmho/m	Water temperature, °C	E_0, V/cm		$j_0 \cdot 10^{-6}$, A/mm²	
					I	III	I	III
1	2	3	4	5	6	7	8	9
72	Shark	38	Sea water	—	—	—	—	77
73	Pike perch	26	14.3	16—18	0.043	0.132	0.062	0.189
74	Minnow	3.5—4.5	—	—	—	—	0.97	1.25—1.43
75	White bream	17.1	15.9	0.2—4	0.026	0.105	0.041	0.167
76		17.9	95	—	0.0179	0.07	0.169—0.01	0.652—0.012
77	Ruffe	10.3	23.8	14—17	0.047	0.218	0.112	0.519
78	Rays	2840 g	Sea water	—	—	—	0.32	0.64—1.2
79	Crucian carp	3—10.5	52.5	—	0.047—0.0286	0.28—0.47	—	—
80		5—7	33	15—16	0.06	0.28—0.26	—	—
81	Carp – crucian carp (hybrid)	5—7	30.3	15—16	0.035	0.315—0.416	0.116	0.954—1.26
82		18	35	3—4.5	—	—	0.099	0.34
83		24	20	6	0.06	0.2—0.25	0.12	0.4—0.5
84	Bream	18.4	15.7	0.6—4	0.025	0.109	0.0492	0.171
85		13.6	19.2	9	0.057	0.212	0.109	0.407
86		13.8	22.3	11—15	0.044	0.253	0.096	0.565

APPENDIX III

Threshold values of field intensity for characteristic reactions (continued).

Item No.	Fish	Size, cm	γ_w, mmho/m	Water temperature, °C	E_0, V/cm		$j_0 \cdot 10^{-4}$, A/mm^2	
					I	III	I	III
1	2	3	4	5	6	7	8	9
87		28.8	57	—	0.055	0.166	0.0316±0.003	0.0926±0.60023
88		21.9	8.6	—	0.0338	0.139	0.029±0.002	0.121±0.0043
89		29.9	20	—	0.0224	0.102	0.044±0.002	0.206±0.0074
90		19.0	40	—	0.0231	0.102	0.09332±0.0029	0.414±0.0119
91		29.5	70.2	—	0.0264	0.101	0.189±0.0082	0.731±0.0303
92		16.7	88	—	0.0215	0.106	0.182±0.0025	0.962±0.056
93		21.7	91.5	—	0.0170	0.086	0.164±0.0097	0.879±0.056
94		31.7	150	—	0.0170	0.081	0.259±0.0083	1.25±0.135
95		37	15.9	0.1—4	0.032	0.091	0.05	0.145
96		43.6	49.5	5	0.0142	0.0432	0.0721	0.218
97		43.2	62.6	7.5	0.0153	0.0474	0.0807	0.250
98		40.4	56.8	10	0.0151	0.0436	0.0867	0.251
99	Burbot	41.1	60.9	12.5	0.0141	0.0397	0.0874	0.243
100		39.7	65.7	15	0.0139	0.0384	0.0925	0.254
101		42.5	8.7	—	0.0335	0.119	0.0296	0.105
102		41.7	41.6	—	0.0218	0.0845	0.0906	0.352
103		40.5	95.2	—	0.0148	0.0743	0.143	0.707
104		4.5—5.5	—	—	—	—	0.36	2.6—3.0
105		23	20	6	0.04	0.0695	—	—
106		20	15.9	1—4	0.030	0.086	0.048	0.137
107	Perch	12	19.5	9—10	0.056	0.212	0.109	0.414
108		11.8	24.1	4—18	0.055	0.254	0.132	0.612
109		27.2	5.7	—	0.062	0.128	0.0356	0.073+0.0018
110		28.5	71.2	—	0.0282	0.0886	0.193±0.01	0.601±0.025
111		20.6	20	6	0.030	0.097	0.06	0.194
112		18.7	15.9	0.4—4	0.026	0.096	0.041	0.153
113	Roach	12.6	24.5	15—18	0.048	0.226	0.117	0.555
114		11.6	27	20.5	0.053	0.267	0.143	0.721
115		13.4	24.9	17	0.045	0.112	0.26	0.647
116	Blue bream	9	—	—	—	—	—	500
117	Skate	450—1120 g	—	—	—	—	0.64	1.28—3
118		250—450 g	—	—	—	—	0.68	1.0—1.6
119		3	—	—	—	—	—	52
120	Scorpionfish	16	—	—	—	—	—	45—65
121		200—400 g	—	—	—	—	0.68	0.8—1.6
122		17.1	24.6	16—17	0.054	0.242	0.133	0.595
123		36.5	24.6	16—17	0.029	0.122	0.071	0.30
124		31.2	90	—	0.0266	0.113	0.025	0.101
125	Pike perch	29.6	174	—	0.0277	0.142	0.0483	0.255
126		34.2	40	—	0.0202	0.0839	0.0815	0.343
127		34.1	93	—	0.0193	0.0726	0.176	0.690
128		40.0	150	—	0.0165	0.0690	0.255	0.994
129		2.5	—	—	—	—	1.58	8.93
130[1]		4.8	25.1	7	—	0.664—1.14	—	1.65—2.86
131[1]		15.6—31.7	25.1	7	—	0.18—0.192	—	4.55—4.83
132[1]		7.6—28	16—28.6	—	—	0.41—0.111	—	—
133	Trout	26.0	35	3—4.5	0.014—0.038	0.05—0.13	0.066—0.083	0.23—0.29
134[1]		15.6	25.4	11.7 (134–136)	—	0.383	—	—
135[1]		20.95	25.4		—	0.100	—	—
136[1]		30.5	25.4		—	0.098	—	—
137		5—7	30.3	15—16	0.0360—0.0258	0.32—0.286	0.108—0.0775	0.961—0.859
137		7.9	25.1	7	—	0.483—0.725	—	1.21—1.82
138	Chinook salmon	62—80	25.1	7	—	0.0741—0.0983	—	0.186—0.246
139		7.87	25.4	11.7	—	0.048—0.073	—	—
140		62.2	25.4	11.7	—	0.074	—	—

Threshold values of field intensity for characteristic reactions (continued).

Item No.	Fish	Size, cm	γ_w, mmho/m	Water temperature, °C	E_0, V/cm		$j_0 \cdot 10^{-6}$, A/mm²	
					I	III	I	III
1	2	3	4	5	6	7	8	9
141		80.0	25.4	11.7	—	0.097	—	—
142		35.4	15.2	0.2—2	0.015	0.079	0.023	0.12
143		32.0	17.4	3.6—4.8	0.018	0.089	0.031	0.155
144		20.1	19.8	9—11	0.032	0.198	0.063	0.392
145	Pike	19.8	25.4	16—19	0.027	0.178	0.069	0.453
146		32	7.9	—	0.0149	0.136	0.0118	0.1075
147		32	17.4	—	0.0144	0.1045	0.0251	0.182
148		32	70.7	—	0.0133	0.0794	0.0938	0.560
149	Ide	13.2	23.5	13—17	0.048	0.247	0.113	0.58
150		11			—	0.25	—	0.7875
151		14			—	0.23	—	0.7875
152		18			—	0.20	—	0.6615
153	Carp	22			—	0.18	—	0.5670
154		26			—	0.16	—	0.5040
155		28	31.5	2—8	—	0.15	—	0.4725
156		10			—	0.380	—	1.19700
157		14			—	0.340	—	0.07100
158	Trout	18			—	0.310	—	0.97650
159		22			—	0.286	—	0.90090
160		26			—	0.276	—	0.86940
161	Baltic herring	15	5.1—7.4%	15	0.020	0.12	—	—
162	Chum, spawners	—	6	2—7	0.025—0.06	0.1—0.19	0.015—0.036	0.06—0.11

Pulsating unipolar current

Item No.	Fish	Size, cm	γ_w, mmho/m	Water temperature, °C	Frequency, Hz	Pulse shape (cf. Figure 63)	Pulse width, msec	E_0, V/cm		
								I	II	III
1	2	3	4	5	6	7	8	9	10	11
163[7]	Eelpout	17—21	—	—	60	*e*	—	—	—	0.28
164	Goby	9.6—10	—	—	5	—	133	—	0.19	0.21
165[7]	Loach	24—27	—		70	*e*	—	—	—	0.27
166[7]	Minnow	7—9	—		90	—	—	—	—	0.24
167		7.6—8.1	—		1	—	500	—	0.25	0.55
168		8—9.5	—	15	45	—	20	—	0.29 (0.32)	—
169		8.1	—		30	—	30	—	0.29	—
170[7]	White bream	12—15	—		40	—	—	—	—	0.32
171	Ruffe	14—16	—	—	50	—	—	—	—	0.21
172[7]	Plaice	23—26	—	—	30	—	—	—	—	0.28
173	Crucian carp	6.6	—	—	45	—	2.22	—	—	1.63
174		6.7	—	—	5	—	133	—	5.40	—
175[7]	Carp	12—15	—	—	50	—	—	—	—	0.21
176[7]	Shorthorn sculpin	15—19	—	15	40	—	—	—	—	0.18
177	Sprat	10	—	—	10	*e*	0.3	0.144	0.24	—
178[7]	Stickleback	6—7	—	15	100	—	—	—	—	0.38
179[7]	Smelt	18—22	—	15	50	—	—	—	—	0.34
180		17	—	15	10	*e*	0.3	0.13	0.45	0.90

APPENDIX III

Threshold values of field intensity for characteristic reactions (continued).

Item No.	Fish	Size, cm	Tw, mmho/m	Water temperature, °C	Frequency, Hz	Pulse shape (cf. Figure 63)	Pulse width, msec	E_0, V/cm I	II	III
1	2	3	4	5	6	7	8	9	10	11
181	Bream	24.3					20	0.06	0.11 (0.24)	0.37
182		26.8			10		90	0.06	0.13 (0.25)	0.31
183		28.4	25—30	13		a	60	0.06	0.10 (0.23)	0.30
184		29.4			5		40	0.06	0.17 (0.38)	0.45
185		29.7			15		60	0.06	0.16 (0.28)	0.36
186[7]	Tench	16—18	—	15	40	—	—	—	—	0.21
187	Burbot	37.4	—	13		e	5	0.25	0.53 (1.07)	1.51
188		40.2	—	13			1	0.56	0.75 (2.30)	3.25
189		40.5	18—20.8	—	5		0.1	0.30	0.71 (3.56)	4.39
190		44.1	—	13		a	2	0.05	0.14 (1.95)	2.29
191		47.8	—	—			1	0.06	0.18 (2.04)	2.93
192[7]	Perch	12—14	—	15	70	—	—	—	—	0.27
193[7]	Orfe	13—15	—	15	30	—	—	—	—	0.2
194	Roach	13.9					2	0.17	0.60 (2.01)	—
195		13.9	18—20.4	13	5	a	2.5	0.17	0.54 (1.60)	—
196		14.0					1	0.18	0.67 (2.06)	—
197	Baltic herring				10		10	—	—	0.22
198					20		5	—	—	0.22
199					40		2.5	—	—	0.22
200		15—19	6—8‰	15	60	e	1.66	—	—	0.22
201					80		1.25	—	—	0.22
202					100		1	—	—	0.22
203					150		0.66	—	—	0.22
204					200		0.5	—	—	0.22
205			5.1—7.4‰		500		0.2	—	—	0.22
206		15		15	6		0.1	0.07	0.13	—
207[7]	Herring	Average	—	15	45	—	—	—	—	—
208	Atlantic mackerel		—	—	5	—	0.5	—	0.65	—
209			—	—	5	—	1.0	—	0.40	—
210			—	—		—	0.14	—	0.62	—
211		26	—	—	10	—	0.5	—	0.53	0.7
212			—	—		—	1	—	0.43	0.51
213			—	—		—	2.0	—	0.36	0.49
214	Sheatfish	14—16	—	15	40	—	—	—	—	0.32
215	Jack mackerel						0.14	0.13	0.61	—
216							0.26	0.09	0.45	—
217							0.5	0.065	0.37	0.82
218		20	35‰	13—14	15	e	1.0	0.055	0.32	0.60
219							2.0	0.04	0.28	0.60
220							0.5	0.14	1.0	—
221							0.5	0.08	0.56	—
222		16.8	—		10		0.3	—	—	0.547
223		17.0	—	27			1.6	—	—	0.261
224		17.0	—		15		1.8	—	—	0.207
225		16.0	—		5	e	8.0	—	—	0.310
226		30.0	—	26.7	10		1.2	—	—	0.206
227		31.5	—	26.7	20		1.2	—	—	0.125
228		14.2	—	24.1	15		0.4	—	—	0.517
229		15.1	—	24.1	10		1.4	—	—	0.483
230	Pike perch	27.0			15		20	0.10	0.205 (0.45)	0.527
231		28.3			15		40	0.087	0.206 (0.43)	0.508
232		28.8					60	0.095	—	0.346
233		28.8	25—30	13	10	e	90	0.087	—	0.341
234		29.5					20	0.074	—	0.39
235		31.6			15		60	0.083	0.204 (0.413)	0.484

APPENDIX III

Threshold values of field intensity for characteristic reactions (continued).

Item No.	Fish	Size, cm	γ_w, mmho/m	Water temperature, °C	Frequency, Hz	Pulse shape (cf. Figure 63)	Pulse width, msec	E_0, V/cm I	II	III
1	2	3	4	5	6	7	8	9	10	11
236	Vimba	25	5.1—7.4‰	15	10	—	0.3	0.033	0.064	0.385
237[7]		Average	—	—	25	—	—	—	—	—
238			—	—	5	—	0.14	—	0.557	—
239			—	—	5	—	7.0	—	0.415	—
240		26	—	—	10	—	0.14	—	0.565	0.692
241			—	—	10	—	0.5	—	0.323	0.461
242	Cod	32	5.1—7.4‰	15	10		0.3	0.032	0.065	—
243		27.6	19.6‰	9—10			0.5	0.076	0.154	—
244		31.0	23.7‰	9—10			0.5	0.073	0.154	—
245		31.0	4.98‰	7	4	e	0.5	0.066	0.117	—
246		31.5	32.9‰				0.5	0.076	0.155	—
247		32	14.8‰	9—10			0.5	0.065	0.143	—
248		32	6.04%				0.5	0.061	0.144	—
249		32.5		13			0.5	0.074	0.138	—
250		33.8	4.98‰	30			0.5	0.077	0.103	—
251		34.2		20			0.5	0.064	0.105	—
252[7]	Tuna	200—300 kg	—	—	7—10	—	—	—	—	—
253[7]	Eel	20—22	—	15	50	—	—	—	—	0.38
254	Trout	10.3	—	—	1	—	500	—	—	0.204
255		10.3	—	—	5	—	133	—	0.201	—
256[7]		15—17	—	15	20	d	—	—	—	0.049

Notes:

1. In experiments with alternating current, except where marked with a "1," the frequency was 50 Hz; where marked it was 60 Hz.
2. The values of δ, E, and γ do not always satisfy the relationship $\delta = E\gamma$, because the three quantities were measured with various methodical errors.
3. The data by different authors were converted by us to the same units of measurement.
4. Only two main reactions are given for alternating current, because most authors do not provide data on reaction II.
5. Since there are no data on the method of measuring E_0 for pulsating current, it remains unclear whether these are peak or effective values.
6. In curve 10 for pulsating current the "beginning" is indicated, and in parentheses the "end" of electrotaxis /142/.
7. In the experiments marked with a "7," the "most advantageous threshold values of the number of pulses" /174,175/ are given.

APPENDIX IV

Aftereffects of Electric Fields on Fish.
(Photocopy of Appendix 5 from Sternin et al. 1976, pages 284-287)

Aftereffects of electric fields on fish (photocopy of Appendix 5 from Sternin et al. 1976, pages 284-287). For water conductivity, 1 mmho/m = 10 µS/cm. Reference 149 is Shentyakova et al. (1970), 202 is McMillan (1928), 210 is Riedel (1954), 163 is Collins et al. (1954), and GosNIORKh is Gosudarstvennyi Nauchno-Issledovatel'skii Institut Ozernogo i Rechnogo Rybnogo Khozyaistva (State Scientific Research Institute of Lake and River Fisheries).

Description of current	γ_w, mmho/m	Water temperature, °C	Intensity of action E_e, converted to E_{e1}, inducing reaction 61 within 1–3 sec	Fish	Length, cm	Duration of exposure, sec	Results of aftereffect (survival, %, etc.)	Time of reverting to normal state, min	Remarks
1	2	3	4	5	6	7	8	9	10
Direct current	28–32	14–16	1	Roach (spawner)	–	20	Ability of normal vital activity and reproduction proved (cf. Table 26)	2–6	/210/
Alternating current, 50 Hz	28–32	14–16	1			20		2–6	
Alternating current, 50 Hz	–	–	5	Chum (spawner)	–	30	The same	–	GosNIORKh
Alternating current, 50 Hz	15–18	12–22	1	Blue bream	6–29	5	Ability of normal reproduction and growth proved	–	Exposure 4 times within two years, each experiment carried out on hundreds of specimens /149/
			1	Roach	6–29	5		–	
			1	White bream	5–9	5		–	
			1	Bream	4–21	5		–	
			1	Perch	18–30	5		–	
Alternating current, 50 Hz	0.4	2.5–5	7	Minnow	3.6–7.0	30	100	10–12 (depression discovered in one specimen after 2 hr)	GosNIORKh
			14	"	3.3–7.3	30	100	10–50 (three specimens had traces of subcutaneous hemorrhages)	Each experiment on 10 specimens
			28	"	3.2–7.5	10	96	15–120	50 specimens
			28	"	3.8–6.6	60	40	60–130	10 "
Pulsating current ("Pelikan" machine) homogeneous field	35	3–7	3.5	Trout	22	30	100		GosNIORKh 20 specimens
			3.5	Carp	24	30	100		
inhomogeneous field			3.5	Trout	22	5	100		
			3.5	Carp	24	5	100	60–90	
			3.5	Trout	22	30	95		
			3.5	Carp	24	30	100		
Alternating current, 60 Hz	25	12	1	Salmon (juveniles)	8	60	100	–	
			1.2			60	100	–	/202/
homogeneous field			1.5			60	90	–	30 specimens
			1.7			60	61		
			2.1			60	43		
			1			300	100	–	
			1.2			300	31	–	
			1.4			300	18	–	
			1.6			300	33	–	
			1.75			300	20	–	

Aftereffects of electric fields on fish (continued).

Description of current	κ_w, mmho/m	Water temperature, °C	Intensity of action E_a, converted to E_{a1}, inducing reaction 61 within 1–3 sec	Fish	Length, cm	Duration of exposure, sec	Results of aftereffect (survival, %, etc.)	Time of reverting to normal state, min	Remarks
1	2	3	4	5	6	7	8	9	10
Rectified direct current	70	12−16	1	Eel	45−70	30	100	0.1	10 specimens in each experiment
			3			30	100	0.3−1.5	
			5			30	100	2−3	
			10			30	100	4−15	
			1	Roach	12−14	30	100	0.3−0.5	
			3			30	85	2.0−3.5	
			5			30	82	4.2−5.3	
			3		3−7	30	83	2.1−3.5	
			5			30	76	4.0−7.2	
			1	Pike	20−24	30	100	0.1−0.2	
			3			30	100	0.5−1.6	
			5			30	100	2.4−3.8	
			10			30	100	6.5−8.5	
Pulsating current of rectangular shape, $f = 2$ Hz, $t_i = 20$ msec	−	10−13	5	Salmon (juveniles)	5−11	30	0	−	Data established from corresponding regression lines plotted according to experimental results /163/
			10			30	93	−	
			20			30	65	−	
			30			30	48	−	
			2			960	96	−	
			2			1,200	82	−	
			4			360	90	−	
			4			600	79	−	
			4			840	67	−	
			8			180	92	−	
			8			360	80	−	
			8			600	62	−	
$f = 8$ Hz			4			60	96	−	
			4			120	85	−	
$t_i = 40$ msec			4			180	62	−	

APPENDIX V

U.S. Fish and Wildlife Service Competency Requirements for Electrofishing Operations and Guidelines for the Safe Construction, Modification, and Operation of Electrofishing Equipment
(Photocopy of U.S. Fish and Wildlife Service 1985)

APPENDIX V

U.S. Fish and Wildlife Service competency requirements for electrofishing operations and guidelines for the safe construction, modification, and operation of electrofishing equipment (photocopy of U.S. Fish and Wildlife Service 1985).

CHAPTER 13

Electrofishing

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13.1 Purpose. To ensure the safe conduct of electrofishing operations by establishing Servicewide competency requirements for electrofishing operations. This chapter also provides guidelines for the safe construction, modification, and operation of electrofishing equipment.

13.2 Scope. The provisions of this chapter apply to all Service activities using electricity (produced by gasoline powered generators/alternators or batteries) to sample animals in aquatic habitats.

13.3 Policy. The Service recognizes the electrofishing operation as a hazardous activity for which skills training is required in accordance with 24 AM 1.7 B (2).

It is, therefore, Service policy that all personnel serving as electrofishing team leaders demonstrate knowledge of the principles and techniques of electrofishing. Team leaders will be considered knowledgeable of the principles and techniques of electrofishing upon satisfactory completion of the National Fisheries Academy course, Principles and Techniques of Electrofishing. In lieu of course completion, Service personnel may satisfactorily complete a certifying examination by the Superintendent, National Fisheries Academy.

13.4 Authority.

A. 29 CFR 1910 - General Industry Standards.

B. Federal Boat Safety Act of 1971 as amended (46 U.S.C. 1451-89).

C. National Fire Protection Association (NFPA) 70-1981, National Electric Code (NEC).

13.5 Definitions.

A. Anode. The positive electrode.

B. Bonding. The permanent joining of metallic parts to form an electrically conductive path which assures electrical continuity, with the capacity to safely conduct current.

C. Branch circuit. The circuit conductors between the final overcurrent device protecting the circuit and the electrical load(s).

D. Cathode. The negative electrode.

E. Circuit breakers. A device designed to open and close a circuit by a non-automatic means, and to open the circuit automatically on the predetermined overcurrent without damage to itself when properly applied within its rating.

F. Deadman switch. A switch which requires constant pressure to supply electrical current to the circuit.

G. Electrofishing. The use of electricity to provide a sufficient electrical stimulus in fish to permit easy capture by netting.

H. Electrofishing team leader. The individual in charge of the electrofishing operation. Only persons demonstrating knowledge of the principles and techniques of electrofishing in accordance with 13.6D can serve as electrofishing team leaders.

I. Ground. A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth, or to some conducting body that serves in place of the earth.

J. Isolation transformer. A transformer inserted into a system to separate one section of the system from undesired influences with other sections.

K. Netter. The individual who nets the captured fish during electrofishing operations.

L. Power control circuit. The circuit which interconnects and adjusts the power from the pulsator or generator to the electrodes.

M. Raintight. Constructed or protected so that exposure to a beating rain will not result in the entrance of water.

N. Variable voltage pulsator electroshocker. The device used to deliver the pulsed electric current.

O. Watertight. Constructed so that moisture will not enter the enclosure.

P. Weatherproof. Constructed or protected so that exposure to the weather will not interfere with successful operation.

13.6 Responsibilities. These responsibilities supplement those found in 24 AM 1.5.

A. Chief, Office of Safety and Security. Will maintain a current listing of all Service personnel possessing an electrofishing certificate of competency, and provide regional safety managers with such listing.

B. Regional directors. Regional directors will ensure that all persons serving as electrofishing team leaders have received from the Superintendent, National Fisheries Academy, a certificate of competency for electrofishing.

C. Superintendent, National Fisheries Academy.

(1) Prepares electrofishing certifying examination for persons desiring to demonstrate knowledge of the principles and techniques of electrofishing by satisfactory completion of a certifying examination in lieu of completion of the National Fisheries Academy course, Principles and Techniques of Electrofishing. The certifying examination may be taken 3 times, in intervals of at least 30 days. Persons failing to satisfactorily complete the certifying examination in 3 attempts will be required to complete the National Fisheries Academy course, Principles and Techniques of Electrofishing, prior to serving as a team leader.

(2) Ensures sufficient scheduling of the course, Principles and Techniques of Electrofishing.

(3) Issues certificates of competency for individuals either completing the course, Principles and Techniques of Electrofishing, or satisfactorily completing the certifying examination.

(4) Provides the Office of Safety and Security with a listing of all personnel possessing an electrofishing certificate of competency and update such listing as appropriate.

D. Electrofishing team leader. Only individuals demonstrating knowledge of electrofishing techniques can serve as electrofishing team leaders. Team leaders will be considered knowledgeable of the principles and techniques of electrofishing upon satisfactory completion of the National Fisheries Academy course, Principles and Techniques of Electrofishing. In lieu of course completion, Service personnel may satisfactorily complete a certifying examination prepared by the Superintendent, National Fisheries Academy. Training and education for electrofishing operations will otherwise be in accordance with section 13.7. As the individuals in charge of electrofishing operations, the team leaders will do the following:

(1) Identify hazardous conditions associated with proposed electrofishing operations, determine measures to protect electrofishing team members, and appropriately brief team members (see section 13.7B).

(2) Ensure that employees have and utilize the proper safety equipment.

(3) Ensure adequate warning is provided to the public to avoid public exposure to the potential hazards of electrofishing operations.

(4) Ensure precautions are taken to avoid harm to pets, domestic animals, or wildlife.

(5) Ensure that all electrofishing operations cease and all crew members go ashore in the event of a thunderstorm.

(6) Ensure that only those persons necessary to conduct a safe and efficient operation, and observers being trained, engage in each electrofishing operation.

(7) Ensure the availability of a well equipped, water-tight first aid kit. Questions concerning the contents of the first aid kit may be directed to the regional safety manager.

(8) The team leader should review the electrofishing considerations checklist found in Exhibit 1, and ensure the addition of specialized items to the checklist that pertain to his/her region or operation.

E. Project leaders. Ensure compliance with the provisions of this chapter.

F. Employee. Report all potential work hazards/accidents/incidents and job related illnesses/injuries to his/her supervisor immediately.

13.7 Training and education.

A. Team leader training and education will cover the areas identified below.

(1) The basic principles of electricity and transmission of current in water.

(2) The basic concept and design guidelines for electrofishing equipment.

(3) Electrofishing equipment and the equipment's capabilities, limitations, and safety features.

(4) The safety precautions to employ while using electrofishing equipment.

(5) The team leader must have a current certification in cardiopulmonary resuscitation (CPR) training and first aid.

Completion of the course, Principles and Techniques of Electrofishing, at the National Fisheries Academy or at a field location, or successful completion of the certifying examination, will serve to satisfy competency for factors 1, 2, 3, and 4. A certificate from the Red Cross or other recognized institution will certify CPR and first aid training.

B. All members of the electrofishing crew will be briefed in the following areas:

(1) Hazards involved in electrofishing.

(2) Safe operation of electrofishing equipment.

(3) Basic emergency procedures for drowning, unconsciousness, and electrical shock.

(4) All members of the electrofishing crew will also be knowledgeable of defensive driving techniques, including towing and backing of boat trailers if an electrofishing boat is used, and safe boating operations.

13.8 Electrical equipment: specifications and operation.

A. General.

(1) Isolation transformer. AC voltage from the generator will be isolated from ground either by removing the ground strap from the generator case or by adding an isolation transformer.

(2) Voltage. Rated voltages of insulation of conductors used to deliver output current from the pulsator to the electrodes must exceed the maximum potential voltage of the pulsator or generator by the next higher rating as follows:

Pulsator/generator	Minimum insulation rating of conductor
0 - 249 volts	250 volts
249 - 599 volts	600 volts
599 - 899 volts	900 volts
900 - 12,999 volts	13,000 volts

(3) Conductor size. Conductor size (i.e., current carrying wire) will be approved for rated amperage of equipment as follows:

Maximum amperage	Minimum conductor size
10	16 AWG
15	14 AWG
20	12 AWG
30	10 AWG

(4) Conductor type.

(a) Conductors will be of the stranded type for flexibility and be suitable for use in dampness.

(b) All conductors in the boat will be enclosed in conduit or liquid-tight, flexible conduit; however, appropriate heavy duty rubber cord can be used where flexibility is desired.

(c) Connectors used in association with flexible cords will be of the locking, waterproof type.

(5) Connections.

(a) Splices in wiring will not be permitted. If connections are necessary, the rating of the connector must be the same or greater than the wire.

(b) All equipment will be turned off before making any connections or replacing parts.

(6) Junction boxes. Junction boxes will be cast iron, cast aluminum, fiberglass, plastic, or rubber. All types must either be weatherproof or raintight depending on use. All junction boxes with switching equipment must be weatherproof. Junction boxes without switches may be raintight.

(7) Circuit breakers.

(a) Power output conductors from the generator or alternator will include a circuit breaker or fuse to provide branch circuit protection.

(b) Circuit breaker or fuses used for providing branch circuit protection will be enclosed in a weatherproof enclosure or cabinet that complies with National Electric Code, Article 373-2, which states the following:

"In damp or wet locations, cabinets and cutout boxes of the surface type will be so placed or equipoed so as to prevent moisture or water from entering and accumulating within the cabinet or cutout box and will be mounted so that there is at least 1/4-inch air space between the enclosure and the wall or other supporting surface. Cabinets or cutout boxes installed in wet locations will be weatherproof."

(8) Electrodes and net handles. Net handles will be constructed of a non-conductive material and will be of sufficient length to avoid hand contact with the water.

(9) Noise. Noise levels will be maintained within the acceptable exposure of 85 dba for 8-hour exposure. Personal protective measures, such as use of earplugs, are described in 24 AM 8. The purchase of sound powered headphones is authorized through station funding. This type of headphor shuts out generator and motor noise and provides clear communication between the netter and equipment operator.

(10) Exhaust from power source. The exhaust from gasoline powered engines and generator alternators will be directed away from the equipment operator. Exposed hot pipes will be enclosed in protective screening to reduce the potential of burn exposure to crew members. The use of galvanized pipe for exhaust is discouraged due to the potential release of toxic gases that are produced under extreme heating conditions.

(11) Fuel storage. Gasoline will be stored and transported in approved metal containers. Such containers when used for storage on metal hull boats will be grounded.

(12) Refueling. To refuel the generator/alternator, all equipment will be turned off. Hot surfaces will be allowed to cool. It is recommended that all tanks be filled prior to each operation to avoid the potential for explosion or fire while refueling hot gasoline engines.

(13) Instruction sheets. Instruction sheets for boat, equipment, and operational procedures will be enclosed in waterproof plastic and be readily available for reference at all times during the electrofishing operation.

(14) Preventive maintenance.

(a) All equipment used in electrofishing will be scheduled for an annual preventive maintenance inspection. In addition, all equipment will be inspected before each use.

(b) Any equipment deficiency which may present a safety hazard will be corrected before each field operation or when equipment damage occurs during actual use.

B. Portable electroshockers.

(1) Electrodes.

(a) Electrode handles will be constructed of a nonconductive material and be long enough to avoid hand contact with the water.

(b) The positive electrode (anode) used with portable electroshockers will be equipped with a pressure switch that breaks the electric current upon release.

(2) Netter position. Netters will work beside or behind the individual with the electrofishing equipment to ensure the electrical field is well in front of both workers.

(3) Standard safety equipment.

(a) All persons using portable electroshockers will wear rubber footwear which will insulate the wearer from electrical shock. All footwear will be equipped with nonslip soles.

(b) Rubber linesman gloves, rated above the voltage being used in the electrofishing operation, will be worn. These gloves will be inspected for punctures before each use and will be replaced at adequate intervals.

(c) Polaroid sunglasses will be worn when there is glare.

(4) Portable electrical power source.

(a) Batteries used as electrical power source for backpack shockers will be of the gel type that will not leak when tipped or overturned.

(b) Backpacks will be equipped with a quick release belt (hip) and shoulder straps.

(5) Power control.

(a) The operator will have a switch to the pulsator or power control unit so that the electricity can be turned off quickly in an emergency.

(b) All equipment purchased after October 1, 1985, must be equipped with a tilt switch that breaks the circuit if the operator falls. The switch must be a type that has to be manually reset after the operator has regained his/her footing.

(6) Personal flotation devices. All persons will wear U.S. Coast Guard approved personal flotation devices (Type II) (i.e., life jackets or float coats) when operating in waters that are deep, high velocity, or turbid, to prevent drowning.

Note: Flotation devices constructed of materials such as ensolite are not bulky and are light weight. This material used in float coats can provide some protection against loss of body heat if the person accidentally falls into cold water.

(7) Hazard awareness. All persons will be aware of the hazards involved in using portable electroshockers in running waters such as slippery surfaces, swift water currents, deep areas, and obstacles such as logs or similar objects.

C. Electrofishing boats.

(1) Design.

(a) Electrofishing boats will provide adequate flotation and freeboard clearance consistent with equipment, cargo, and passenger weight when being operated. The boat will be equipped to meet U.S. Coast Guard or State boating regulations.

(b) The boat deck will be painted with a nonslip or skid resistant coating.

(2) Clear working space. General boat housekeeping must provide adequate working space to conduct safe operations. Care will be exercised to prevent clutter that may result in safety hazards.

(3) Boat inspection before each use. The boat and equipment will be visually inspected for safety by the supervisor or operator in charge prior to each use. Significant deficiencies, which could result in employee injury, will be corrected prior to operation or use of the equipment.

(4) Controls for electrical equipment.

(a) Electrical amp-volt meters will be installed to provide adequate monitoring of boat electrical power equipment.

(b) The boat operator should be able to operate an electrical control or switch to cut the power in case of an accident.

(c) The netter will have a deadman switch connected to the power control circuit from the pulsator or generator source. This allows the current between the electrodes to be broken in case of an accident.

(d) Power control circuits will not exceed 24 volts.

(5) Grounding/bonding. All metal surfaces within a metal boat will be electrically connected, grounded, and bonded to the boat hull to eliminate differences in electrical potential that may result in electric shock. The metal boat hull may also be used as a cathode.

To avoid possible electrolysis problems when the metal hull is being used as a cathode, zinc strips should be attached to the hull as "sacrificial anodes." The electrolysis will occur on the zinc strips which will preserve the integrity of the hull.

(6) Battery enclosure. An acid proof, nonmetallic enclosure and holder will be provided for wet cell batteries.

(7) Conductor protection. All conductors may be installed in a common raceway (conduit) provided each conductor installed is continuous (without connectors, breaks, or splicing), is independently and correctly insulated. All low voltage (24 volts or less) circuits will be contained in separate raceways from those containing high voltage conductors.

(8) Auxiliary circuits. Lighting and other auxiliary circuits should not exceed 24 volts. Note: 110 volt lamps may be used if the lamp is shielded with a nonconductive cage.

(9) Lighting.

(a) When the boat is to be operated at night, adequate on-board lighting (12-24 volts) will be provided for working areas.

(b) Adequate lighting will also be provided while electrofishing to avoid safety hazards such as striking logs, rocks, and overhead tree branches.

(10) Safety rails. Safety rails will be provided around the outside of the netting area and will be at least 42 inches high and be constructed of at least 3/4-inch diameter heavy-walled steel pipe or 1½-inch heavy wall aluminium pipe. Rails will be so designed to withstand a 200-pound side thrust. The work deck will be covered with nonskid material and sloped to allow drainage. The high gunnels of wooden draft boats are satisfactory as safety rails.

(11) Fire extinguisher. Each boat will be equipped with at least one 5-pound type ABC fire extinguisher mounted in a holder for easy access to the boat operator and away from high fire potential sources.

(12) Personal flotation devices. All occupants will wear U.S. Coast Guard approved personal flotation devices at all times. Life vests that meet the requirements of Type II are designed to turn an unconscious person in the water from a face downward position to a vertical or slightly backward position. Float coats may provide some protection against the loss of body heat if the person were to accidentally fall into the cold water.

(13) Standard safety equipment.

(a) Hip boots will be worn so they can be easily removed in case the boat capsizes.

(b) Rubber chest waders will also be worn when necessary in order to remain dry as protection against electrical shock.

(c) Rubber gloves will be worn that are rated above the voltage being used. These will be inspected before each use and replaced at adequate intervals.

(d) Polaroid-type sunglasses will be worn to reduce glare from the water.

(14) Color coding/labeling of significant hazards. To ensure visibility, the color red will be used to identify fire extinguishers, safety cans, and stop buttons for electrical equipment. The color fluorescent orange will be used to identify all other safety switches.

Electrofishing Considerations Checklist

ITEMS	DATE	OK YES/NO	COMMENTS
1. Employee training			
A. Electrofishing			
B. Cardiopulmonary resuscitation			
C. Defensive driving skills			
D. Safe boating practices			
2. Electrical equipment			
A. General			
B. Conductors			
C. Connections			
D. Junction boxes			
E. Circuit breakers			
F. Electrodes			
3. Noise exposure			
A. Determination of exposure			
B. Use of personal protection equipment			
4. Exhaust from power source			
5. Fuel storage			
6. Refueling			

APPENDIX V

U.S. Fish and Wildlife Service competency requirements . . . and guidelines (continued).

ITEMS	DATE	OK YES/NO	COMMENTS
7. Preventive maintenance			
8. Portable electroshockers			
A. Electrodes			
B. Netter position			
9. Standard safety equipment			
10. Portable electrical source			
11. Power controls			
12. Personal flotation devices			
13. Electrofishing boats			
A. Design			
B. Clear working space			
C. Inspection before use			
D. Electrical equipment controls			
E. Grounding			
F. Battery enclosure			
G. Conductor protection			
H. Auxiliary circuits			
I. Lighting			

U.S. Fish and Wildlife Service competency requirements . . . and guidelines (continued).

ITEMS	DATE	OK YES/NO	COMMENTS
J. Safety rails			
K. Fire extinguisher			
L. Personal flotation devices			
M. Standard safety equipment			
N. Color coding			
14. Public safety			
15. Other considerations			
A. First aid kits			
B. Weather conditions			

APPENDIX VI

Suggestions for Future Development of Boat Electrofishing Gear and Techniques

SUGGESTIONS FOR FUTURE DEVELOPMENT OF BOAT ELECTROFISHING GEAR AND TECHNIQUES

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Assuming safe and effective electrofishing fields are identified, new electrofishing gear and techniques may be necessary to help minimize adverse effects and maintain effective intensity and size of the field. Field intensity and size can change significantly with habitat, water conductivity, and water temperature. Response thresholds for the target species and size group also vary with water conductivity and temperature. To maintain an effective field of consistent range from one site or study to the next, and even within sites, the size of the electrodes and especially the power output to them must be adjusted frequently. Even if present electrofishing practices do not cause significant harm to target species, these advances could improve the comparability of data by equalizing capture efficiency.

Development of the following ideas could facilitate calculation of optimal fields on a site-by-site or continuous basis for manual or, eventually, automatic adjustment of output and electrode size to maintain consistent capture efficiency. Although conceived for boat-electrofishing operations, some ideas could be adapted for other electrofishing applications. Costs and concern for reliability are the principal impediments to these developments, but all are feasible with today's technology.

I. Develop a computer program for field use to map approximations of electrofishing fields or provide necessary information to maintain a predefined field.
   A. In-water voltage-gradient measurements (or control-box settings), water conductivity, and electrode descriptors, would be used to produce a calculated map of the anodic field.
   B. Experimentally determined field attributes for a safe but effective field for targeted fish, along with the water conductivity and temperature of the site, would be used to determine appropriate combinations of electrode size and control-box settings.
   C. With appropriately positioned in-water sensors, the program could be modified for use by a control-box computer to continuously maintain the desired field.

II. Develop an array of sensors for continuous monitoring of water conductivity, temperature, and voltage gradients or full waveform information at specific locations relative to the anode(s).
   A. Sensor data would be displayed on the electrofishing control box to continuously monitor these parameters for manual adjustments of the field. Eventually, sensor data could be fed to a control-box computer to maintain the desired field automatically.
   B. Voltage-gradient or oscilloscope sensors would be positioned in very specific locations and, if necessary, incorporate a mechanism to maintain their orientation along the lines of current.
   C. The sensor array could also provide other useful information such as water depth which could help define the vertical range of the field.
   D. Voltage-gradient data from these sensors would to be displayed or input as peak rather than average or root-mean-square values.

III. Develop size-adjustable electrode systems to minimize the zone of tetany and optimize the zones of taxis and narcosis in waters of varying conductivity.

A. Consider semi-free-floating hemispherical, half-submerged spherical, hemicylindrical, or dropper-array anodes as alternatives to currently preferred spherical and dropper-array anodes.

1. Such electrodes could incorporate a floating ring or plate that would maintain a constant amount of exposed surface area immediately below it and the water surface.

a. With currently used electrodes positioned at the surface, the submerged surface area can vary as the electrodes bob in and out of the water or as the boat changes speed or direction. This in turn rapidly changes the size of the field and its intensity near the anode.

b. With currently used electrodes positioned to remain below the surface, the depth and near-surface shape of the most intense portions of the electrical field can vary. Changes in electrode depth could also affect the ease with which fish are netted.

2. Such anodes would direct all the current along and away from the surface whereas a fully submerged spherical electrode would direct half of the current towards the surface. If the latter results in wasted energy or an undesirable current distribution at the water surface, the floating hemisphere or hemicylinder concepts might be particularly advantageous.

3. The anodes could be suspended on vertical guides from a lightweight frame fixed well out from the bow of the boat or raft.

a. These guides would maintain the anodes in a constant horizontal position relative to the boat.

b. Hydraulics or a winch could be employed to raise them from the water when traveling between sites.

B. Consider designs for easily changing the effective size of the anode(s).

1. The amount of electrode surface exposed to the water and perhaps the effective diameter of the electrode could be varied by adjustable insulating covers over portions of the anode surface(s).

a. Such adjustable covers might be particularly suited to a long hemicylindrical anode (with quarter-spherical ends). The insulating cover could extend out from or be drawn in toward the middle, effectively creating two variable size anodes.

b. Covers that slide down around a hemisphere would effectively change both surface area and diameter of the anode.

c. Insulated sleeves could be slid over the cylinders or cables of a dropper array.

2. In the case of dropper arrays, mechanisms could be devised to continuously vary the effective diameter of the array.

3. With such electrodes, exposed surface area and effective diameter could be adjusted manually as needed or automatically and continuously, in a more advanced arrangement under computer control, to maintain the desired field.

IV. Develop other electrode modifications that might further minimize injury to fish or improve capture efficiency.

A. Protective, non-conductive grids around electrodes might prevent fish from directly contacting the electrodes or entering the zone of tetany

B. Underwater lights on or near the anode might improve capture efficiency when electrofishing at night. The light should enhance visibility for netters and might attract certain species to the effective field.

V. Develop a computerized electrofishing control box ("black box") using a modification of the above described program and input from a sensor array for automated control of electrical output and electrode size to maintain the desired field. This control-box computer would be similar in concept to computers on today's automobiles that control fuel mixture, timing, transmission shifting, braking, and traction based on sensor input and driver options.

A. The electrofishing team would input desired field strength (e.g., voltage gradient at the position of one or more sensors) or simply specify the target species and size range. The control-box computer would then determine optimal field characteristics (based on experimentally determined thresholds), and with sensor input, adjust output and electrode size to approximate the desired field.

B. Within certain limits, this system would instantaneously adjust control-box output and electrode size in response to changes in conductivity and temperature. It might also be able to adjust for changes in channel configuration and substrate conductivity.

1. This would help minimize otherwise uncontrollable changes in the field that make the field either less effective or more harmful to the target fish.

2. It would account for a large number of variables and maintain constant effective fields that could be replicated in various waters. In doing so, it would dramatically improve the comparability of data based on catch per unit effort.

C. The computer could display a continuous visual diagram of current waveform and parameters (oscilloscope input) and approximate field size and shape.

D. The system could warn users when settings for target species will jeopardize the welfare of other species or size groups.

E. The system would automatically shutdown whenever problems develop or the system cannot compensate for environmental changes. This would prevent damage to the generator and control-box, injury to fish by stronger than desired fields, and operation of the system when electrical conditions are unsafe. The computer might even be able to identify the source of the problem and suggest steps to remedy the problem.