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New Perspectives in Electrofishing

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Edited by S.M. Allen-Gil

U.S. Environmental Protection Agency
National Health Effects Research Laboratory
Western Ecology Division
200 S.W. 35th Street
Corvallis, OR 97333

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Foreword

By Dixon Landers

Measuring and evaluating the natural environment with its inherent variability in time, space and, where applicable, animal movement and behavior, is a daunting task. Electrofishing techniques have been widely used for several decades in assessing various attributes of fish populations and their relationships with human activities as well as natural habitat features. Recently, there has been increased emphasis placed on evaluating the quantitative aspects of the electrofishing approaches and the injurious effects they may have on individual fish as well as fish populations. Moreover, since these are widely used techniques and they are perceived to be generally "nondestructive," many researchers will continue to use them and submit scientific papers and technical reports for publication which are based on these techniques. The Western Ecology Division (Corvallis, Oregon) of the U.S. Environmental Protection Agency's National Health and Environmental Effects Research Laboratory convened a workshop of electrofishing experts, equipment designers and manufacturers, practitioners and researchers in April 1997, to focus in on the key elements, issues and concerns relating to electrofishing. This week-long workshop included basic electrofishing technical background as well as practical field applications in lentic and lotic waters.

The attendees found the workshop highly successful as judged by the amount of information covered, its current relevance and the diverse range of topics competently addressed by the participants. Therefore, the US Environmental Protection Agency agreed to publish the proceedings of the workshop as a technical report. The moving force behind the workshop and this report is Dr. Susan Allen-Gil, currently at Ithaca College, NY. She not only organized the entire workshop but worked closely with all the section contributors to produce the final product, this report. She also edited the report and created a summary.

This report is not an exhaustive treatment of electrofishing theory, technical issues and science but it does attempt to present the basics as they are currently viewed by experts in the field. Controversial areas and unresolved issues are addressed and not sidestepped in this report. Viewpoints are presented from the perspectives of the two dominant manufacturers of electrofishing equipment in the United States, Coffelt, Inc. and Smith-Root, Inc. A very useful list of scientific references cited is provided, as well as a supplemental list of references for the serious student of electrofishing. This report addresses two key elements in the electrofishing arena: a perspective of the relative effects of electrofishing as compared with other fish assessment techniques, and guidance on what types of important auxiliary information should be reported along with the results of electrofishing efforts. It is the hope of the authors, as well as the sponsor of this report, that readers of this document will find it relevant, current and informative.

Dixon H. Landers
Senior Research Environmental Scientist
USEPA, Western Ecology Division

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Introduction

By Susan Allen-Gil

Electrofishing is one of the most common techniques used in freshwater fisheries research. The U.S. EPA, as well as most state agencies, employs electrofishing as the primary method for assessing fish communities in stream monitoring programs. Yet, though electrofishing is a common sampling method, many research biologists and field technicians lack a thorough understanding of electrofishing theory, equipment configurations, sampling design, and data interpretation considerations.

In our own research through the U.S. EPA's Western Ecology Division, in fast-flowing alluvial rivers in western Washington and in alcoves of the Willamette River in Oregon, we encountered several difficulties and uncertainties in optimizing our raft electrofishing configuration, implementing our sampling protocol, and interpreting our results. In discussing these difficulties and uncertainties with colleagues at other state and federal agencies and universities, we found they shared our concerns.

Furthermore, when we examined studies in peer-reviewed literature, we found that most did not provide enough information on how electrofishing was conducted for us to evaluate electrofishing efficiency and data quality. Since electrofishing is partly science and partly art, it may be possible to replicate results but impossible to achieve full comparability between studies performed by different crews using different equipment in different conditions. There is room, however, to expand our understanding of electrofishing principles, to improve our sampling designs, and to communicate our methods and interpretation of results more clearly and completely to other fisheries biologists and environmental managers.

Our motivation to convene a week-long workshop on electrofishing perspectives was twofold. First, we wanted to educate ourselves and our regional colleagues on how to optimize electrofishing practices. Second, we hoped to develop and promote guidelines for electrofishing and enhance our ability to evaluate electrofishing results from our studies as well as those of others.

To achieve our goals, we assembled nationally recognized experts in several aspects of electrofishing, including theoretical and applied scientists, electrofishing engineers, and manufacturers. Jim Reynolds is an expert in electrofishing theory and practice. As the leader of the U.S. Fish And Wildlife Service's (USFWS) Cooperative Fishery Research Unit at the University of Alaska in Fairbanks, Jim studies the ecology, dynamics, and assessment of freshwater fish populations in Alaska. He has published extensively on electrofishing techniques, and has taught numerous workshops on electrofishing for the USFWS. Lee Carstensen is the chief engineer at Smith-Root, Inc. John Sharber, an electrical engineer, is the owner of Coffelt Manufacturing, Inc. Peter Bayley is an assistant professor in the Fisheries and Wildlife Department at Oregon State University who has published extensively on the efficiency of different gear types used in fisheries research. Robert Hughes is a senior staff scientist with Dynamac, Inc. His major research interests are regional aquatic ecology, from state to national scales, and fish assemblage ecology, particularly the use of fishes to assess ecological integrity and regional patterns. Chip Andrus is a hydrologist and freshwater fish habitat specialist with Dynamac, Inc. He conducts field research on fish use of alcoves on the Willamette River, using day and night electrofishing.

We believe this report provides a breadth of information and discussion that is not available from any other single source. We present information on electrofishing theory, equipment, sampling design, and interpretation of electrofishing data. In the first chapter, Jim Reynolds reviews major theoretical and practical considerations and techniques for testing electrofishing performance in the field. In the second and third chapters, Lee Carstensen and John Sharber discuss general and specific design features of electrofishing equipment and its use. In the fourth and fifth chapters, Peter Bayley and Robert Hughes address issues related to sampling and interpretation of electrofishing data. Chip Andrus presents sampling design considerations for specific environments in the sixth chapter. The final chapter is a synthesis and summary from a discussion among leading electrofishing experts, manufacturers, and fisheries biologists on several current electrofishing issues, including species-specific injury and mortality rates, standardization of parameters reported in peer-reviewed manuscripts, and consideration of operator licensing and imposed restrictions of electrofishing practices. The report does not exhaustively cover all aspects of electrofishing. Readers seeking additional information should refer to the annotated bibliography in the appendix.

Chapter 1 – Electrofishing Theory

By Jim Reynolds

Our parents told us never to mix water and electricity. However, water and electricity can be mixed safely. This is the underlying premise of electrofishing. However, considerable knowledge and care must be employed to electrofishing to ensure that neither the operators nor the fish are injured. The knowledge required includes an understanding of both some basic electrical principles and the properties of water.

Safe and effective electrofishing requires an understanding of the basic principles of *electrical circuit theory* and also of *field theory*, which is the study of electrical energy dissipated into a three-dimensional medium—in this case, water. Most people who electrofish spend much of their time focusing on circuits: boat wiring, electrical units, metering, and other hardware aspects of electrofishing. However, we must also understand field theory to apply electrofishing principles correctly. Based on what happens in sampling situations, electrofishing mythologies emerge that may not have anything to do with electrical principles. Table 1 provides basic terms and definitions useful in the discussion of electrofishing.

Table 1. Terminology Used in Electrical Circuit Theory and Field Theory

TERM	DEFINITION	SYMBOL	UNITS
Electrical charge	Quantity of an electrical current	Q	coulomb
Voltage	Energy/Charge	V	volt
Current	Charge/Time	I	ampere (amp)
Resistance	Electrical friction	R or (omega, Ω)	ohm
Power	Energy/Time	P	watts
Energy	Power x times	W	watt-hour
Resistivity	Friction x distance	p (rho, ρ)	ohm-cm
Conductivity	1/P	sigma, σ	mho/cm or µS/cm
Voltage gradient	Change in voltage over distance	$\mathcal{E}$	volts/cm
Current density	Flow of charge carriers through a plane	J	amp/cm^2
Power density	Power dissipated in a three-dimensional medium	D	watt/cm^3

Circuit Theory

An understanding of the basic concepts of matter and its relationship to charged particles is the first step. Matter consists of electrically charged particles, called electrons (-), protons (+), and neutrons. Although all matter contains electrically charged particles, most matter is at a neutral charge. Electricity is caused by separating the charged particles, and electrical energy is then created by the attractive forces between protons and electrons.

A second important concept is the transfer of electrical energy, which requires the creation of a circuit. A circuit is a closed, insulated system that allows electrical energy to travel along a particular pathway. As an analogy for a circuit, imagine a conveyer belt with a coal mine at one end and a power plant at the other. On this conveyer belt, there are buckets that carry a quantity of coal from the mine to the plant. Because of mechanical restrictions of the engines driving the conveyer belt, it travels at a constant speed. The buckets on this belt are all the same size and are spaced at regular intervals. However, the power plant operator wants to produce more energy. The options are to add bigger buckets, more buckets, or both. In our analogy, the buckets are the charge carriers. The coal is the energy in a latent form. Energy per charge and the number of charge carriers coming through the system at a time can be adjusted. Increasing the bucket size would increase the energy per charge (voltage) of each carrier. Current is charge per unit time, or the number of buckets coming down the conveyer belt. The constant speed of the conveyor belt is analogous to electricity, which moves at the speed of light. Thus, only the energy per charge (voltage) and the charge per time (current) can be changed. In electrofishing systems, usually only the voltage is adjustable, but adjusting voltage often results in changes in current.

There are two kinds of circuits: series and parallel. In a series circuit, resistors, or loads, are arranged sequentially in the circuit; if one load is removed, the whole system shuts down. In effect, the loads become switches if they stop working. In this type of system, current is constant through all the loads, and voltage is variable, assuming that the loads are different in size. Total voltage is equal to the sum of voltages at all resistors. The total resistance of an electrofishing circuit, or "equivalent resistance," is the sum of all the individual resistors or loads. In a series circuit, this is the sum of the individual resistances.

Problem 1: We have a series circuit in which we have two resistors, R_1 = 20 ohms and R_2 = 30 ohms. Applied circuit voltage is 100. What is the equivalent resistance? $R_{eq} = (R_1 + R_2) = 20 + 30 = 50$ ohms. What is the current flowing through the system? Current = I = voltage/resistance = V/R_{eq} = 100 volts/50 ohms = 2 amperes (amps). The voltage at R_1 is: $V_1 = I \times R_1 = 2(20) = 40$ volts at the first load. The voltage at $R_2 = V_2 = I \times R_2 = 2(30) =$ 60 volts. If we add these together, the total applied voltage is 100. Double-checking the current at each resistor: Current at R_1: $I_1 = V_1/R_1 = 40/20 = 2$ amps. Current at R_2: $I_2 = V_2/R_2 = 60/30 = 2$ amps.

This example illustrates the characteristics of a series circuit. Current is constant in the system, but voltage varies if the resistors have different values. Changing the resistance in a system alters the relationship between voltage and current. Current is greatly reduced in a system with high resistance. The energy dissipates as heat in the circuit, overheating the wiring and the loads.

Parallel circuits differ from series circuits in that they have branched pathways. Each branch usually has a resistor, and the resistors are not a sequential system as in a series circuit. The current splits at each branch. In the series circuit, current is constant and voltage varies. Parallel circuits are the opposite: voltage is constant and the current is variable at each load, when the loads have different resistances. When all loads have equal resistances, the voltage is the same at each resistor. Overloading one of the loads does not interrupt the total flow of energy; other loads continue to function. Parallel circuits are used in buildings to prevent the "Christmas lights effect," in which the failure of one bulb means that the whole string becomes nonfunctional until the failed bulb is located and replaced. Another advantage is that constant voltage can be maintained in parallel circuits, delivering 110 to 120 volts to each pathway. The current varies depending on the load. The equivalent resistance of a parallel circuit is calculated as the inverse of the sum of the inverses for all the systems' resistors.

Returning to Problem 1: $R_1 = 20$, $R_2 = 30$, and the applied voltage is 100, but R_1 and R_2 are in parallel. Knowing this, the equivalent resistance can be calculated. $R_{eq} = 1/[(1/20) + (1/30)] = 12$ ohms. The current is $I = V/R_{eq} = 100/12 = 8.3$ amps. The current flowing through each resistor is $I_1 = V/R_1 = 100/20 = 5$ amps, $I_2 = V/R_2 = 100/30 = 3.3$ amps. The total current is $I_1 + I_2 = 8.3$ amps.

As recently as 1950, scientists believed in the conventional flow theory, in which electricity flows from the positive to the negative and protons carry the electrical charge. Since then, physicists have proved that electrons carry the electrical charge and that the direction of flow is from negative to positive, a principle known as electron flow theory.

Ohm's Law states that resistance is a constant ratio between the voltage and the current. Imagine a container filled with water, with a faucet on the bottom for releasing water. The pressure created by the volume of water and the force of gravity provides a total force that pushes the water out at some rate. This pressure is analogous to voltage. The rate of water flow from the faucet represents the current. In this example, the size of the faucet's opening is also important. The opening creates a restriction to the flow, which is analogous to resistance in electrical circuits. Increasing the water level in the container would increase the pressure, resulting in increased flow. The ratio, however, between the pressure of the water (voltage) and the rate of water flowing from the faucet (current) remains constant, regardless of the voltage or the applied pressure (amount of water in the container).

With this basic knowledge of circuits, it is possible to construct an electrofishing system, at least on paper. The system has two anodes (positive electrodes) and one or more cathodes. For metal boats, the boat hull often serves as the cathode, or dropper cathodes as used. The anodes are positioned off a boat's bow, or, for backpack shocking units, at the end of the rod. The fishing and netting occurs at the anode.

If an electrofishing system were configured as a single series circuit, removal of any of the loads would interrupt the circuit, which implies that taking any of the anodes out of the water should cause electrofishing to stop. This does not occur because the anodes are in a parallel circuit within a larger series circuit. If there is only one cathode, however, removing it from the water interrupts the circuit and terminates electrofishing. If there are multiple cathodes, configured as droppers, for example, they occur in a parallel circuit in the same manner as the anodes, so that electrofishing continues when some droppers are not suspended in the water. This brief description applies to most electrofishing systems.

The basic concept for circuit layout of an electrofishing system is straightforward. It involves both parallel and series circuits. The overall resistance of the system can be calculated by first simplifying the parallel circuits into equivalent resistances, which reduces the system to a series circuit in which the total resistance is the sum of the individual resistors. The basic difference between electrofishing systems and the circuits described here is that water replaces some of the wiring and the load of interest is the fish.

Problem 2: An electrofishing system has two anodes with resistances of 75 and 50 ohms. The cathode is bigger and it has a resistance (R_c) of 10 ohms. Applied voltage is 200 volts. The equivalent resistance (R_{eq}) of this electrofishing system is determined by first calculating the equivalent resistance of the anode parallel subcircuit (R_a), which is the inverse of the sum of the inverses: $R_a = 1/(1/75 + 1/50) = 30$ ohms. Then the total equivalent resistance is $R_{eq} = R_a + R_c = 10 + 30 = 40$ ohms, and the current (I) = $V/R_{eq} = 200/40 = 5$ amps.

The objective in electrofishing is to transfer energy from one load to another, from water to fish. The resistance of the fish is generally different than that of the water. The difference between the resistance of the water and the resistance of the fish can act as a barrier to energy transfer. The input effort in electrofishing is limited by the ability to control the available energy in the water. Factors regulating the energy transfer from water to fish are beyond our control, but understanding the factors allows us to respond intelligently.

Another important concept in electrofishing is power (P), which is energy per unit time. Power is voltage × current, where voltage is energy per unit charge and current is charges per unit time. Canceling out the charge leaves energy per unit time. Joule's Law is: $P = I \times R$, or $P = V^2/R$.

Problem 3: In the electrofishing boat example, there was an applied voltage of 200, with 75 ohms resistance for one anode, 50 ohms for the other, and 10 ohms for the cathode. The equivalent resistance for the system was 40 and the current for the system was 5 amps. The power is: $P = 200 \times 5$ amps = 1000 watts. Given that 746 watts equals 1 horsepower (hp), 1000 watts equals 1.3 hp.

Figure 1 summarizes the relationships between the four parameters associated with a circuit: voltage, resistance, current, and power. All relationships are logarithmic. Using this graph, if two values for two variables are known, we can approximate the two remaining variables.

Problem 4: For the electrofishing boat example, resistance was 40 ohms and current was 5 amps. Using Figure 1, the intersection of these two isolines occurs at a voltage of approximately 200 and a power of 1000 watts.

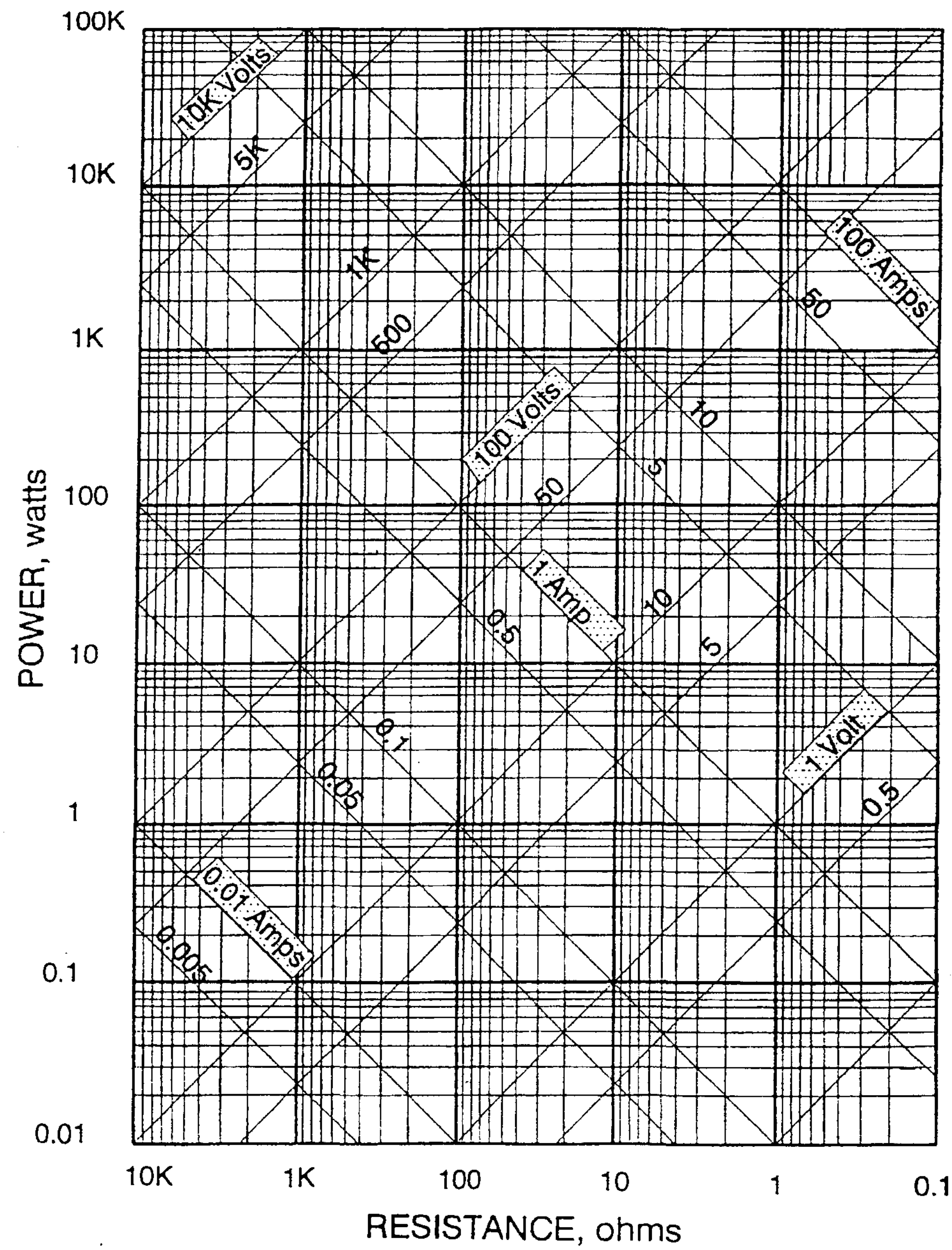

Figure 1. Summary of relationships between the four parameters associated with a circuit: voltage, resistance, current, and power.

Waveforms

A trace graph of voltage in a circuit with an operable switch would show an instantaneous increase (because electrons travel at the speed of light) when the switch was closed and an instantaneous decrease when the switch was opened. This is called direct current (DC). Electrons flow in one direction from the cathode to the anode because the polarity never changes. The simple DC waveform is characterized only by the voltage. A trace graph of the current would be identical to that for the voltage.

For many years, DC was considered a good waveform for electrofishing because it was less harmful to fish than some other waveforms. Producing DC, however, requires maintenance of high power inputs with a large, heavy generator. More recently, pulsed DC has been employed in electrofishing. Pulsed DC is produced by the regulated interruption of the continuous flow of DC which yields a pulsed signal. Pulsed DC is also effective at delivering energy to the water, and is less traumatic to fish than other waveforms, but it also has the advantage of not requiring continuous high-energy inputs. Most electrofishing systems do not produce a classical square pulsed DC waveform, because pulsed DC can be produced in a variety of ways. More circuitry and system components add to production costs, but some pulsed DC waveforms are less expensive to produce than others.

Pulsed DC is more complex than DC. Waveforms are characterized by the maximum voltage (V_{max}) and an average voltage. Current follows the same general pattern as voltage. Determining the average voltage is difficult; it depends not only on the maximum voltage, but also on the duration and spacing between pulses, which is usually in milliseconds (msec). In electrofishing, 5 msec is a typical pulse time, referred to as the pulse duration or pulse width. The number of pulses per unit time is called pulse frequency, pulses per second, or hertz (Hz). The typical frequency of an electrofishing unit is 50–60 Hz.

It remains uncertain which factors are most important in fish response to pulsed DC. It may be average voltage or peak voltage, overall power, or a combination of all of these variables. It appears that peak power and peak voltage are important. Fish do seem to respond to peaks, but if the peaks are not wide enough, they do not respond at all. Fish response, therefore, must be a function of some combination of peak power and average power, where power delivered is determined by both voltage and current.

Another type of waveform is alternating current (AC), which is characterized by a switch in polarity. AC is the waveform output of most generators. The direction of the polarity changes at the generator's speed, which is usually 60 Hz (60-cycle AC). If AC is used in an electrofishing system where the two electrodes are the same size and shape, both electrodes will have the same fishing effect. Fish are not drawn by one electrode more than the other.

AC waveforms are characterized by peak voltage and peak-to-peak voltage, which is the difference between the positive peak and negative peak. The average voltage is meaningless, because adding the positive side and the negative side yields an average of zero. Therefore, root mean square (RMS) voltage is used to characterize AC waveforms. RMS voltage (V_{rms}) is the most common output format on electrofishing and voltage meters. A typical sigmoid AC waveform produced by a generator has a peak voltage (V_p) equal to the RMS voltage (V_{rms}) divided by 0.707. The peak-to-peak voltage is 2 × V_p, or 2 × (V_{rms}/0.707) = 2.6. Therefore, the peak-to-peak voltage is nearly 3 times the V_{rms} voltage. V_{rms} voltmeters are common on electrofishing units, which is very important, because fish react to the peak-to-peak voltage. AC power energy can also be detrimental to fish because of the changing polarity. A fish orients to the positive in a DC system. In an AC system, fish cannot orient to the positive 60 times a second, which is the rate of the polarity switches in a typical electrofishing system. The fish enters oscillotaxis, characterized by quivering and unpredictable reactions. Sometimes, in low-conductivity waters, the only way to catch fish with electrofishing is to use AC. To achieve the same results with pulsed DC would require a bigger generator to put more energy into the water, which sometimes is not feasible. The general recommendation in electrofishing, however, is to avoid using AC if possible, because it poses a greater threat of injury to humans and fish alike.

A relatively inexpensive method of producing pulsed DC is to rectify the AC waveform. By cropping the waveform to only the positive half, a pseudo-pulsed DC waveform is produced at the generator's cycle speed. A 60-cycle generator would produce 60-Hz pulsed DC with equal amounts of time on and off. The duty cycle is the percentage of time on during a waveform cycle, which would be 50% in this example. This waveform is called a half-rectified AC form. To fully rectify an AC form, the negative portion of the waveform is flipped to the positive. This produces a pulsed DC form because it returns to zero after each pulse, and is always positive. It also doubles the frequency.

Most electrofishing units take AC from the generator and produce a continuous DC, then break it up into various patterns. This function provides the most flexibility in terms of frequency, duty cycle, pulse duration, and amplitude. The biggest limitation of these systems is the inability to vary the pulse shape. The choice of pulse shape influences cost of production; exponential decay waveforms are fairly inexpensive to produce. Among pulse shapes, a square wave has the greatest area under the curve, and thus maximized power output for a given voltage. Other waveforms have lower average power or average voltage given the same peak.

Minimizing the area under the curve, or using less power, is one way to minimize injury to fish. One of the most popular approaches at present is to emit "pulse trains," or "a pulse energy packet," or "a low-energy waveform," rather than regular pulses. These newer waveforms are characterized by short duration spikes, are clumped in time, and are produced at a high frequency (>200 Hz). The "packets" are then produced at a low frequency (10–20 Hz). The result is a low-frequency pulsed DC with less energy in each packet than in an equivalent pulse. The objective is to reduce the rate and severity of injury by eliciting the same response from the fish using less energy.

Most electrofishing units provide a means of adjusting parameters, such as frequency, within the pulse. Although an adjustment may help maximize catch and minimize fish injury in research studies, it requires the operator to track the parameters during field electrofishing so that population modelling can account for parameter differences. If population models that include these variables are not used (i.e., some monitoring programs), then the operational parameters need to accompany the presentation and comparison of catch data among sites.

Most electrofishing units do not provide a means of viewing the emitted waveform, thus it is useful to examine the output waveform with an oscilloscope. Equipment should be checked with an oscilloscope to permit detection of AC effects such as a negative spike in a pulsed DC waveform. Not all pulsed DC electrofishing systems use a true pulsed DC signal, and changes in equipment and components that occur with aging can alter emitted waveforms. Battery-powered units are more prone to AC component waveforms. The on/off switching of the pulse causes an overshoot. Correcting this problem is expensive, and the problem is not usually present in older backpack units. Only an oscilloscope will reveal whether (or not) a pulsed DC waveform has negative spikes. On most scopes, overshoots appear as a very faint line. Overshoots can be 2–3 times greater than the pulse in magnitude, but are usually of short duration (microseconds). Fish can be harmed by these overshoots (negative spikes).

Using traditional pulsed DC systems (not low-energy waveforms) to catch adult fish (>20 cm), the duty cycle should be maintained at 50% or lower. A duty cycle of 10–15% would be preferable if it were successful in catching fish. Ideal frequencies are 20–25 Hz, and frequencies above 100 Hz should be avoided because they will harm adult fish of all species. Frequencies of 50–60 Hz are very injurious to adult salmonids. Most backpack and boat units provide a 50% duty cycle and 50 Hz as a "standard" waveform; it is desirable to be able to control not only voltage, but also frequency and duty cycle (or pulse duration).

Fish Response and Sensitivity

All fish have approximately the same nervous system, which is similar to those of other vertebrate species. In a dorsal view, the nerves follow the myomeres out from the spinal cord and integrate the muscles. The front of the brain appears to carry a negative charge, which may explain why fish are attracted to anodes. The nerve angles and lengths appear to be important determinants of electrofishing, because the orientation of the fish to the electrical field determines how the fish is affected.

The objective in electrofishing is to interfere with this neurological pathway between the brain and muscles of the fish. By blocking the internal signal and overriding it with a signal from the water, electrofishing current redirects the neurological signal and muscular reaction. Fish can swim undisturbed through an electrical barrier if they are oriented in particular positions. Likewise, once in the electrical field, the behavior of a fish varies with its orientation. The optimal reaction is involuntary swimming in a predictable direction (toward the anode). If the force of contraction is too great, however, spinal injuries may occur.

Electrofishing is size selective. Larger fish tend to be more vulnerable because their length spans a greater voltage gradient (referred to as "head to tail" voltage). Consider the pulse traveling in a wave length; a larger fish intersects more wave lengths and more energy. There is also a dorsal-ventral vector. It is important to think in terms of power, rather than voltage or current, because power encompasses the waveform in the water. The power wave goes through the water too, and affects the fish from different vectors. Although the mechanisms are not completely understood, it is known that orientation is also important.

There is an important distinction between size selectivity in capture efficiency and mortality. While capture efficiencies usually increase with fish length, mortality is more closely related to responses to pulse frequency and duration. Differences in skeletal and muscular structure among species and size classes may influence susceptibility to injury. Another important difference between species is the extent and nature of scales. For example, salmonids are very finely scaled and have little resistance to energy transfer. A heavily scaled fish such as a carp, on the other hand, is more resistant at the same energy level. Proportion of muscle mass relative to the total body weight may also be a factor. Weak swimmers have a very low proportion of muscle mass, probably below 50%. Strong swimmers, such as migratory species, have well above 50% muscle mass. In salmonids, this proportion is high (60%). A higher proportion of muscle mass increases the response to applied electricity.

Many unanswered questions remain. The stability of the conductivity of the fish is not known, but is assumed to be constant for a given species and size group. According to power theory, energy transfer is greatest when the conductivity of the fish is similar to that of the water. While conductivity in water can be readily measured, conductivity of live fish can only be estimated.

We do not fully understand the relationship between power transfer theory and pulsing waveforms. In electrofishing, however, it is useful to think of energy in terms of power, which is energy per unit of time, in much the same way as we refer to energy for home use as watt hours, also energy per unit time. Power, not pulse length, dictates fish response. We talk in general terms using energy, but it is actually power that pertains to electrofishing effects.

Basic Electrofishing Systems

Figure 2 diagrams the basic layout of an electrofishing system. In battery operated units, the battery produces continuous 12-volt DC power. If the electrofishing unit served only to interrupt the power, a peak pulse of 12 volts would be produced, but this is not enough power to stun fish. The power, either from a battery as pulsed DC or from an AC-producing generator, is then put through a transformer, which enhances the input signal to produce a higher output signal. Pulsing the battery signal is necessary to prevent the transformer from burning out. The transformer treats pulsed DC signals in the same manner it treats AC signals. The transformer produces a high-voltage AC signal. For AC electrofishing, this is all that is required. Therefore, the simplest systems are composed of a battery, a DC:AC inverter, and a small transformer. These systems are not very powerful, but they do create an AC signal suitable for electrofishing. Routing the electricity through an AC to DC converter provides a high DC signal. The addition of a pulser provides a high-pulsed DC waveform.

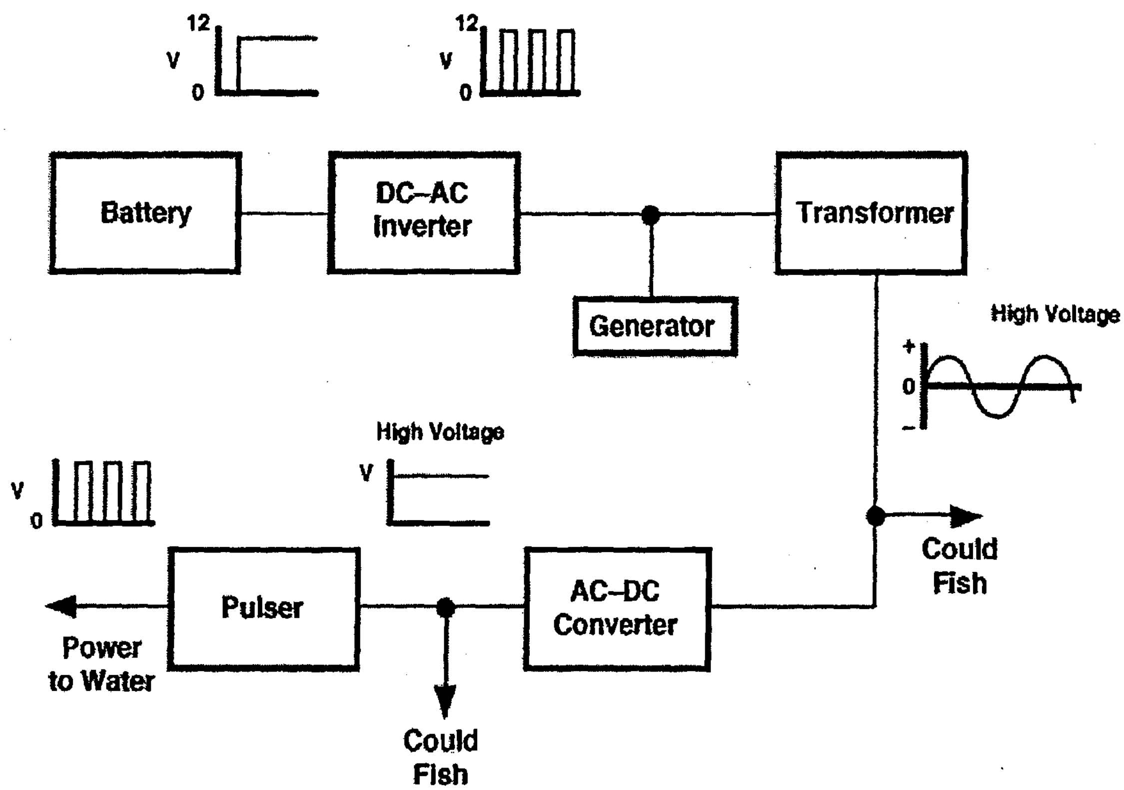

Figure 2. The basic layout of an electrofishing system.

Maximum Power Transfer

In circuits, there are two types of loads or resistances: the internal resistance of the system and a load resistance. A critical concept in electrofishing is maximum power transfer, which occurs when the internal resistance is equal to the load resistance.

Problem 5: A series circuit has an internal resistance (R_g) of 10 ohms and a variable load resistance (R_v). The applied voltage is 120. The following equations for circuits apply:

P (power) is equal to $I^2 \times R_{eq}$
$R_{eq} = R_g + R_v = 10 + R_v$
I (current) is equal to $V/(10 + R_R)$
$V_v = I \times R_v$
$P_v = I \times V_v$

Table 2 demonstrates that in a system with a constant internal load, the power produced is variable in a nonlinear pattern. As resistance increases, current decreases and voltage increases. Power, however, increases and then decreases, illustrating the principle of maximum power transfer. The maximum power transfer occurs when R_v is equal to 10. Maximum power transfer occurs when the load resistance is equal to the internal resistance, which is a circuit phenomenon. This principal applies directly to electrofishing: the variable load is the fish and the load is the water. In real situations, however, both loads are variable.

Table 2. Maximum Power Transfer Determination

R_R (resistance)	I (current)	P_R (power)	V_R (voltage)
0	12	0	0
5	8	320	40
10	6	360	60
14	5	350	70
20	4	320	80
50	2	200	100
	0	0	120

For practical purposes, the resistance of the electrical system, whether it is a backpack or a boat, is nominal relative to the water. The significant resistance is in the water and in the transfer to the fish. When the "resistances" (i.e., conductivities) of the fish and the water are equal, any power put into the water will be fully transferred to the fish. In electrofishing practice, it is not possible to know if a matched condition exists. In some instances, even if conductivities are equal, the power delivered to the fish may not be sufficient to elicit the desired reaction. This principal, however, does explain why fish can be caught on one occasion but not on another, in the same place, and with the same equipment. The matching of the conditions may have changed enough that the power put into the water has effectively dropped below transfer threshold from water to fish. This usually occurs when the water conductivity changes. An electrofishing system may work well at 360 watts on one occasion; but then, on a repeat visit to the site, more wattage may be needed. This phenomenon could be caused by a change in water conductivity, related to rainfall, water temperature, or time of day, which changes the ratio of fish and water conductivities.

The idea of achieving constant power is important for establishing electrofishing guidelines. Assuming that fish conductivity is constant, knowledge of water conductivity and temperature are required to standardize the power level. The power in the field can be determined using Figure 3. The Y axis is the percent of maximum power transfer. The X axis is the ratio of resistance load to internal load (i.e., ratio of fish and water conductivities). At a ratio of 1, power transfer is 100%. At ratios of 2 or 0.5, 90% power transfer is obtained. Although it seems that power transfer between low-conductivity water and high-conductivity fish ought to be maximal, this is not true. Fishing at high conductivity is as hard as fishing at low conductivity, assuming the range of water conductivity is much wider than the range of fish conductivity. For practical purposes, fish conductivity is treated as a constant of about 150 mohms/cm, based on previous research. Although this constant was determined in goldfish, and may not be representative of all fish species, it has been helpful in evaluating the importance of standardizing for power. By standardizing power to water conductivity, as much as 15% of the variability in catch per unit effort (CPUE) can be explained. Given the variability in CPUE can vary considerable among samples, it is important to reduce variable to the extent possible through standardization of equipment and procedures.

People electrofishing in low-conductivity water (~<50 µS/cm) tend to be "volt" people, because the current meter doesn't respond in low-conductivity water. People who fish in high-conductivity water (~150 µS/cm) tend to be "amp" people, because the voltage meter doesn't change much. At low conductivities, there is very little change in current density, but a large change in voltage gradient. At high water conductivities there is little change in voltage gradient lines, but large changes in current density. Regardless, we fish with power— the product of volts and amps—which is why understanding power transfer theory is so important to understanding problems in electrofishing.

The amount of power that must be added to match a previous electrofishing effort can be determined using Figure 4. Inverting the y-axis changes the percentage to a ratio, which is termed the power correction factor (PCF). The PCF is the additional power needed over the present situation to achieve a given power transfer. The equation for PCF is: $PCF = (1 + q)^2 / 4 \times q$, where q is the ratio of fish conductivity and water conductivity.

To illustrate, suppose we had been fishing in perfectly matched conditions at 320 watts, and we returned to find a mismatch. In other words, we had been fishing successfully and assumed a match of 1, but upon our return, the water conductivity was twofold higher. The additional amount of power required to achieve matched conditions would be calculated as the wattage (320) × the current matched power ratio (1.1). Therefore, 352 watts would be required to achieve the same power transfer. While standardizing the power transfer among sampling efforts is very important, actually doing so is often beyond the capabilities of existing electrofishing equipment. For example, it may not be possible to adjust the voltage as precisely as would be required in this example. Nonetheless, testing the settings prior to starting a depletion estimate study is extremely important to reduce variability. Also, population estimation models typically do not allow for changes in settings among passes.

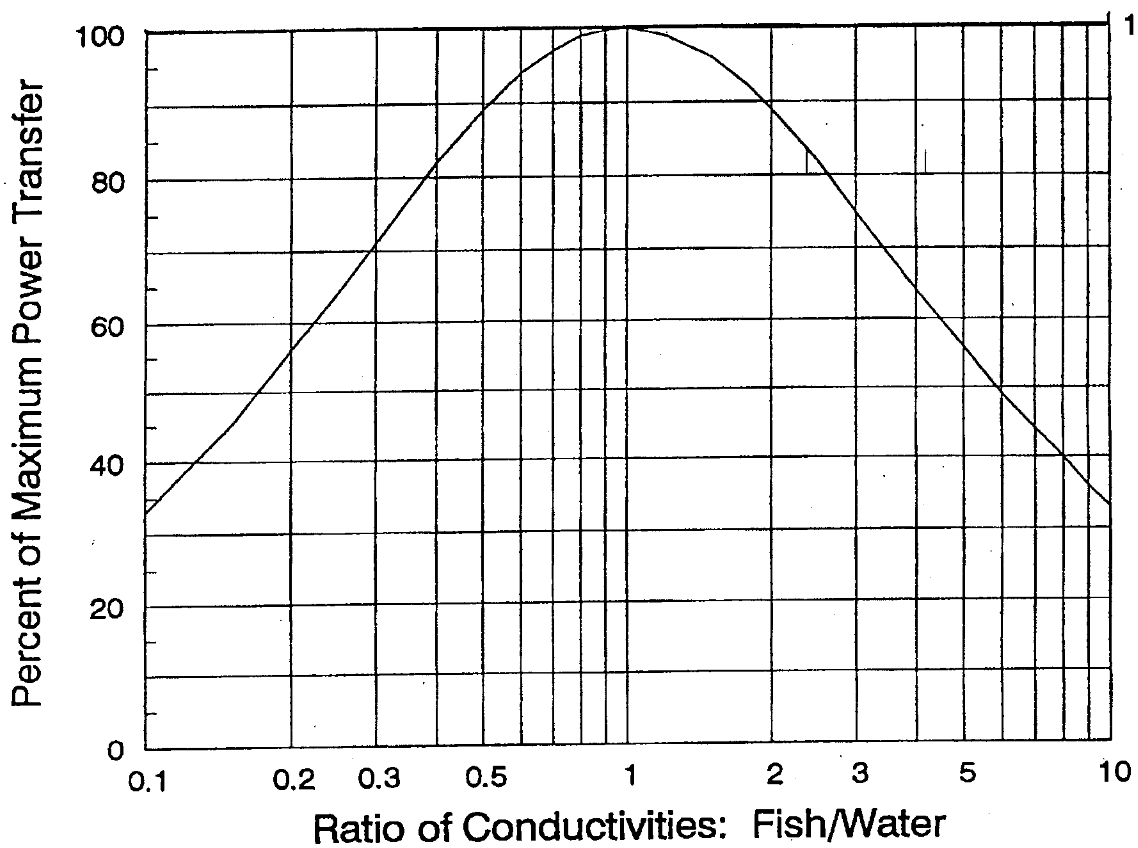

Figure 3. Relationship between conductivity of fish and water and maximum transfer of power to fish.

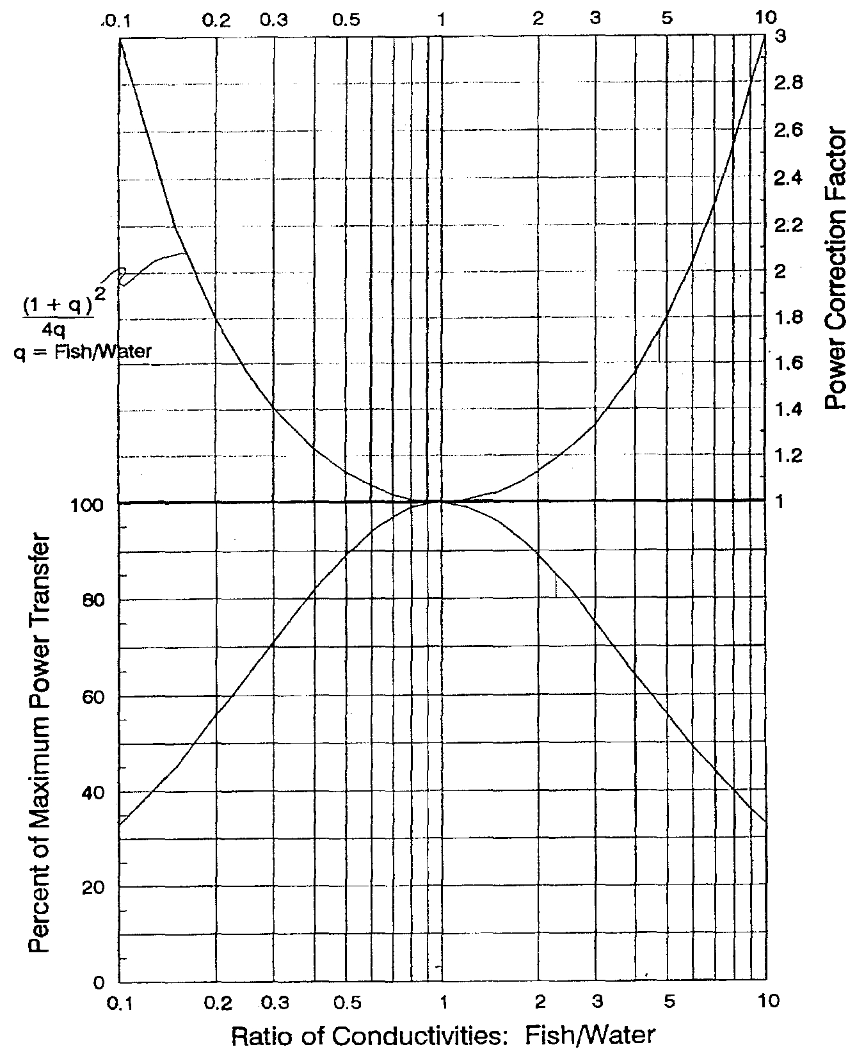

Figure 4. Adjusting power to match a previous electrofishing effort. A doubling the water conductivity between sampling efforts resultys in a decrease of the fish/water conductivity ration from 1 to 0.5. Thus, a power correction factor of ~1.1 is required to achieve the same power transfer. (If 320 watts were applied at the first sampling, 352 watts would need to be applied during the second sampling to maintain equal power transfer.)

Diagnosing Electrofishing Systems Using an Oscilloscope

Internal system aging manifests itself in an electrofisher as the need to change settings to achieve the same effect. When a system drifts beyond the adjustment capabilities of the unit, internal parts may need to be replaced.

An oscilloscope should be used on electrofishing units once a year to calibrate the settings and output meters to the waveforms emitted, and to detect defects. It is critical that the oscilloscope be supplied with an independent power source, and not run off the same generator that is powering the electrofishing unit.

The output of an oscilloscope can be used to calculate frequency, as well as peak and average voltage. The goal of electrofishing is to use the minimal amount of energy required to elicit a reaction from the fish. It is best to start with a low frequency and a fairly narrow pulse width, and increase the amplitude as necessary until the fish react. If this does not work, start over with a higher frequency until results are obtained. It is a good idea to compose a table of setting voltage vs. real voltage and attach it to the unit. It would even be possible to connect an oscilloscope to the anode and cathode during electrofishing to monitor the power waveform. Power density determines the effective range of electrofishing systems. It can be determined using a field strength or voltage gradient meter. While many fish biologist feel that such procedures are excessively time-consuming, undertaking these analyses prior to the field season can significantly improve the interpretability of electrofisahing data.

Although it is not possible to know directly if the maximum power transfer condition is occurring during electrofishing, it is helpful to monitor the fish reaction at different voltage settings, and determine the power output (voltage × current). From this, it is possible to build up a database for water and species in an area of interest.

One source of variability is the equipment. Electrofishing units of the same model from the same manufacturer may emit significantly different waveforms (even if the products meet the manufacturer's standards), probably as a result of change in components during the production period. Therefore, every unit purchased should be characterized with an oscilloscope.

Electrical Field Theory

Most electrofishing studies have focused on electrofishing effectiveness in terms of circuit theory. Only recently has there been an emphasis on the characteristics of the electrical field itself. In a three-dimensional medium, distance becomes important. In the analogy of a tank full of water with an outlet pipe, resistance is determined by both the outlet pipe's length and the inside surface area. The resistance is inversely proportional to the inside surface area, but it is directionally proportional to the length of the pipe. The inside surface area represents the viscosity. An equation for the resistance in terms of area and size is: r (resistivity) = P_l / P_A, where P_l=pipe length and P_A=inside surface are of the pipe.

The term resistivity is used instead of resistance to indicate that measurements occur in a field rather than in a circuit. Resistance has no "distance" term, and is measured in ohms. Resistivity (electrical friction) units are ohm/cm. Just as the inverse of resistance is conductance, the inverse of resistivity is conductivity. Conductivity is a measure of how well electricity flows through a three-dimensional medium, and is usually measured in Seimens/cm (S/cm). Because the ion concentration in water is low, conductivity is typically measured as micro-seimens per cm (µS/cm). The two factors that affect water conductivity are ionic strengths and temperature. As ionic strengths increase, so does conductivity. Conductivity affects current density, but has no effect on voltage gradient, if applied voltage remains constant. The ambient conductivity is the important parameter in electrofishing, but it is also essential to record water temperature, because fish physiology is sensitive to changes in temperature.

Other important parameters in field theory are voltage gradient, or volts per cm, and current density, or the current expressed per cm^2. Current density is the flow of charge carriers through a plane. This is the second form, or field form, of Ohm's Law. Electrical fields in water have a very strong nonrandom orientation.

Power density is another important concept in electrical field theory. The product of voltage gradient (e) and current density (J) is equal to power density (D) or watts per cubic cm. Power density is the power dissipated in a three-dimensional medium ($D = e \times J$). Neither power density nor current density can be measured directly, but they can be calculated from field measurements of voltage gradient and conductivity. Current density is equal to $(\text{voltage gradient})^2 \times$ water conductivity. Within an electrical field in water, water conductivity is typically constant because it is a function of water temperature and the amount and type of suspended solids. Water conductivity, however, will vary as the chemical composition of the water varies. Tributaries or point-source disharges can affect the conductivity of receiving waters. By contrast, the voltage gradient differs with distance from the anode. Maximum voltage gradient is used to derive current and power densities.

In most systems, half the total voltage is achieved at the midpoint between the anode and the cathode (Table 3). The voltage gradient, however, is not linear, but changes more rapidly near the electrodes. A plot of the voltage between the two electrodes would be symmetrical because the two electrodes are the same shape and size. Energy dissipates from the two electrodes at the same rate in terms of distance. Although the voltage gradient is the same at the cathode and anode, this does not mean that fish react in the same manner; the neuro-physiology of the fish directs them toward the anode.

The rate of change in voltage over distance is the voltage gradient. Voltage gradient measurements in water are symmetrical, with the highest values at each electrode, and the lowest value halfway between the electrodes. Depending on the spacing of the electrodes and the strength of the field, the voltage gradient can be zero in some areas. Mapping the voltage gradients at different distances from the anodes is an important performance evaluation technique in electrofishing. If anodes and cathodes are separated by too great a distance, then areas of inadequate power density result. Also, a rough rule

Table 3. Voltage Data Taken Between Two Electrodes 25 Centimeters Apart

Distance from first anode (cm)	Volts (V_{rms})
0	0
1.3	6.5
2.5	7.8
5	9.3
7.6	10.1
10.2	10.8
12.7	11.3
15.2	11.8
17.8	12.5
20.3	13.2
22.9	14.1
24.1	16.6
25.4	23.8

of thumb is that effective electrofishing occurs at voltage gradients of 0.1 to 1 V/cm in water of moderate conductivity (200–300 µS/cm). Below 0.1 V/cm, fish tend to escape and above 1.0 V/cm, fish tend to be traumatized. For any given applied voltage and electrofishing configuration, the field strength or voltage gradient mapping remains constant, despite changes in water conductivity. Voltage gradient at any point in the electrical field is directly proportional to applied voltage.

Although the mapped voltage remains constant, the power density changes as a function of conductivity. The characteristics of the field change whenever the position or orientation of the electrodes is changed, which may occur, for example, when cathodes drag along the stream bottom. This can occur with changes in bottom substrate and water velocity.

Electrode Configurations

In a pulsed DC system, the practical depth limit of a dropper acting as an anode to attract fish is about 0.5 meters. The goal is to bring fish to the surface so they are easier to see and net. Droppers are more effective at greater depths for AC systems, and also when the anodes in a pulsed DC system are not effectively attracting fish. With an AC system in very low-conductivity water, steel cable or cylindrical droppers on the stream or lake bottom in 10–15 feet of water can stun fish, causing them to float to the surface.

An effective application for deep cathodes is in deep-sided reservoirs, where a 10–15-foot cable the last foot of which is not insulated is dragged along the bottom. This agitates fish from deeper water into the anode field, where they are then attracted to the anode, which is close to the surface.

A general rule is that cathodes should have a surface area equal to or larger than that of the anodes to prevent wasting power to the cathode in a DC system. The cathode ideally should be much larger than the anode. In backpack shocking units, the small "rat tail" cathodes may have a smaller surface area than the ring anode; in this case, the cathodes are not optimal because they dissipate too much power at the cathode. One way to improve the performance is to increase the size of the cathodes. Screwing two cake pans together, with styrofoam in the middle, is an inexpensive and practical technique for increasing cathode size for backpack units.

Electrode design is a very important but often overlooked feature in electrofishing systems. Different electrode designs fulfill different objectives. A general guiding rule is that electrodes should be made of material as large in diameter as possible, given the voltage inputs. An electrode made from larger diameter material (cable or chimes - hollow cylinders) provides a bigger field that is less damaging to fish. Anodes are usually configured as either cable or chime droppers, but both have the same effect for a given surface area of material. A single dropper 3mm in diameter produces a very intense field close in, with almost no field further out, resulting in large dead areas. The result is that a fish does not react until it gets right next to the anode, then it feels the full force. Therefore, single droppers are not recommended except when fishing in extremely high- or low - conductivity waters, where minimal anode surface area is required to prevent generator overload. If generator overload is not a concern, then droppers of 12-25 mm are advisable. Increasing the diameter of the droppers decreases the intensity of the field near the anodes and extends the distance of the effective field.

Anodes come in a variety of shapes and sizes. A sphere provides uniform (multi-directional) energy dispersal. Large diameter spheres, however, are impractical in most situations because of the weight and drag they impose. An alternative is a large ring with droppers, often referred to as a Wisconsin ring. In the 1960s, Novotny and Priegel (1974) conceived that the addition of anodes suspended from a ring would result in an electrical field similar to that generated by a sphere, because the weak individual fields generated by the droppers would overlap. The disadvantage of Wisconsin rings is that the sphere effect does not occur close to the droppers; therefore, the problem of intense fields close to individual anodes still applies. If fish are netted as soon as they enter the effective field, than this problem is not encountered. However, sweeping a net of fish close to the anodes can expose the fish to the full effect of an intense field.

The effective depth of anodes is determined by the fact that charge carriers are emitted only from metal surfaces perpendicular to that surface. For cylindrical droppers, the electrical field is only as deep as the electrodes, because the surface area on the bottom of the dropper is very small.

The distance between the anode and the cathode is usually not important. When the anode is effective at attracting fish, the cathode acts only as a return circuit for the system. For bankside shocker systems in which the generator is on the bank, the cathode can be buried to provide a good earth contact. When the anode is ineffective at stunning fish, decreasing the distance between the anode and cathode can increase field strength by overlapping the two fields. There is a danger in doing so, however, because equipment damage is likely to occur if the anodes and cathodes touch.

Safety

There is an effort to implement a nationwide inspection and certification program for electrofishers for safety and standardization purposes. For many state and federal agencies, safety is becoming more critical.

More fish biologists have been killed driving to the work site than have been electrocuted. More fish biologists also have been injured by the scare of an electric shock, which caused them to fall and hurt themselves in the boat or on the ground, than from the shock itself. In the United States, since World War II, only about five electrocutions during electrofishing have been documented. Nevertheless, electrofishing can be hazardous; therefore, safety must always come first. In other parts of the world—China, for example—where systems are extremely primitive and people are untrained, the mortality rate is much higher.

The most hazardous type of operation in electroshocking is bankside shocking. Most bankside shocking systems include multiple anodes. The operation is usually large, and untrained personnel may volunteer to operate one or more of the anodes. That's how most people have been killed while electrofishing.

Backpack shocking and boat shocking operate on different safety considerations. In boat shocking, an equipotential surface should be maintained inside the boat. In this condition, a person can touch two metal objects in the boat and not be affected, because everything within the boat has the same potential. In backpacking shocking, it is not possible to maintain equal potentials; therefore, insulation is the only form of protection. The crew leader of an electrofishing effort should be able to affirmatively answer the question, "If an accident occurred, could I defend my procedures?" in front of an objective, investigative body.

Many electrofishing crews use anodes as dipnets. While this practice can be effective and successful if fish are immediately transferred to an assitant netter with a non-conductive handled net and insulated gloves, failure to remove the fish immediately from the intense eletrical field can be harmful to the fish, because the collected fish stay in the net close to the anode and remain exposed. It also can be potentially dangerous for people. Suppose the anode handler is using an anode modified as a dip net, but forgets to switch off power because the fish are coming fast and furious. When the netter swings the live anode with fish and dumps it into a bucket; someone's hand may be in or near the bucket, and that person could be shocked if not properly protected. This technique also disrupts the electrical field every time the anode net is removed from the water to transfer fish to a collection bucket. A net on the anode can be helpful, however, in creating currents in deep pools to move the fish around, increasing their contact with the electrical field.

For electrofishing operations with large crews, the supervisor should not directly participate in the fishing. A real-life example illustrates this point. In an operation with a generator floating in a small raft towed by one crew member, someone else was operating the anodes and still other members were conducting the dip netting. The anode had a net, and the person operating the anode was netting as well. The crew chief was farther out in the stream looking for stray fish and picking up fish on the edge of the field. Yet another crew member was walking along at the stream edge with a bucket into which all the netters were placing the fish. The plastic bale on the bucket handle was missing and the bucket carrier was holding the metal bale with his bare hands. The person operating the anode net came over to dump some fish into the bucket, forgetting to turn off the power, and touched the bucket handle with the anode. The bucket holder was electrified, and fell into the water, which was about 6 inches deep. The dip netters who saw him rushed over to help, with their live anodes still in the water. The crew chief, seeing what was happening, ran to the raft and shut the power off. Although the netters had kill switches on their anodes, they didn't think to let go of them. Later, when asked if he was conscious and aware of what was happening, the bucket handler replied that he knew perfectly well what was going on, but could not get his arms underneath himself to push up. All he could think about was drowning in a few inches of water.

This event illustrates how personal injuries can occur during electrofishing. However, when proper safety precautions are used by trained personnel, the frequency of occurrence of electrofishing accidents is very low.

Standardization

There are three primary sampling strategies, each suitable for different objectives: (1) increasing accuracy by reducing bias, (2) increasing precision by reducing variance, and (3) increasing the specialization or changing the scope of sampling from a general survey to a specialized sampling that targets a particular size group or species.

Many state and federal agencies are particularly interested in standardization of electrofishing protocols. The New York Department of Environmental Conservation, for example, has developed an excellent standard operations procedural manual for centrarchid sampling (Green, 1989).

One way to improve standardization is to develop tables that relate minimum power, water conductivity, and voltage output. Using these graphs, it is possible to insure that fishing power is maintained under different conditions. To do so, however, requires metering of both output peak voltage and output peak current. These meters are not standard on most commercial electrofishing units. However, such meters can be added at additional cost.

The use of surprise tactics (e.g., turning power on after entering an area with abundant fish cover) is very effective for improving efficiency. In streams in the midwest, large fish are very adept at escaping electrofishing capture by using available cover.

Failure to effectively shock areas of abundant cover results in a catch skewed toward smaller fish. Another tactic to improve standardization is to surround cover features with block nets.

Field Testing of Electrofishing Equipment

Calibrating and testing the performance of electrofishing equipment in the field is an extremely important step in standardizing electrofishing practices and in providing the essential information for accurate data interpretation. The recommended method for calibrating electrofishing equipment is mapping the voltage gradient field. This is done by taking measurements of voltage gradients at varying distances from the anode(s) using either an oscilloscope or peak voltage detector.

A useful piece of field-testing equipment is a peak voltage gradient detector. Although the detector does not provide information about the shape of a waveform as does an oscilloscope, it is easier and faster to use in the field. One of the most useful tools is a voltage gradient meter that measures peak voltage. It consists of a probe and detector, which can be plugged into any voltage reading device. A.L. Kolz (National Wildlife Research Center, 3550 Eastbrook Dr., Fort Collins, CO 80525) has developed the detector, and although it is not produced commercially, he will provide anyone who requests it, the specifications for construction. The probe has two exposed metal screws located 5 cm apart. The circuitry automatically divides by five to provide voltage gradient (V/cm). It has two ranges: 1x for 1–5 V/cm, and 10x for up to 50 V/cm. It has a spring-loaded circuit breaker, so it will not stay on accidentally and drain the two 9-volt batteries. Holding the probe parallel to the anode gives the maximum voltage gradient, and rotating it 180° yields an equal but negative reading. Holding it perpendicular usually corresponds to a lower reading, more in line with the isovoltage lines.

Taking voltage gradient measurements at the anode provides information about the maximum power output. Determining the distances from the anodes at which the voltage gradient is equal to 1 V/cm and 0.1 V/cm provides an estimate of the extent of the effective electrofishing range, based on studies using goldfish. Although the rule of thumb for effective field strength is 0.1 to 1 V/cm, it is unclear whether a similar general rule applies for fish injury or mortality. One opinion is that voltage gradient does not affect injury rates. According to this opinion, once a fish is held in the field and is reacting to it, it becomes epileptic. This means that the best way to prevent fish injury is to use low-energy waveforms. The other opinion is that voltage gradient is a very important factor in injury rates since voltage gradients clearly influence rates of fish stress. The difference in opinions centers on a disagreement of the cause of injury. Insufficient data and lack of peer review on the subject prevents conclusive support of either of these opinions.

An audio amplifier can be used to detect the presence and frequency of electrical current rather than risking injury by touching the water with the fingers. Information from voltage gradient probes and oscilloscopes can be used to assess waveforms and map field characteristics. For example, oscilloscopes can detect leading edge spikes on waveforms.

If these spikes are not inherent in the operation of the scope (some scopes are unable to reproduce fast rise waveforms), then the spikes may indicate equipment failures such as probe malfunction, presence of additional electrodes, or a collapse in the field at some location.

Modifying the array of electrodes changes the shape of the field. For example, if the droppers of an umbrella array are spread out more, the overall field strength and shape changes. If the resistance of an electrode system changes, such as through corrosion build-up on the electrodes, field strength is diminished. For this reason, electrodes should be polished periodically.

Electrical field maps for several boat and backpack shockers were evaluated during the workshop. For the first boat unit, a peak voltage gradient of 0.1 V/cm occurred at 0.7 m from the anode. For a second unit, the field extended to 3 m using the same applied voltage setting. This difference in performance has also been seen for backpack units of the same model and manufacturer. Some possible explanations are:

1. Cathode configuration. The more powerful system used the boat as a cathode while the lower powered system used dropper cables for a cathode.

2. Power availability at the anode. There may be differences in the distribution of power in the system. Large cathodes may be able to drive power through a system more efficiently.

3. Anode configuration. When two anodes are located near each other, they may act like a single, larger anode.

It would be helpful to store waveforms in an oscilloscope, so that two units could be compared to help explain observed voltage gradient differences.

The importance of conductivity and temperature should always be considered. Conductivity is the single most important environmental factor in electrofishing. Conductivity cannot be estimated based on water clarity or color. It is dependent on the area's geological characteristics and anthropogenic inputs. Although conductivity is an important determinant of power density, it does not affect the voltage gradient mapping of a field. In mapping voltage gradient fields, it is important to operate the same electrode configuration with the same applied voltage. Doubling the applied voltage should result in a field of the same dimensions, but with voltage gradient readings twice as high, because the dimensions of the field are determined by the geometries involved. Temperature has a separate biological effect; it affects the ability of the fish to float, respond, and escape.

Chapter 2 – Electrofishing with Smith-Root Systems

by Lee Carstensen

Models 12B (Battery Powered) and 15D (Generator Powered)

Smith-Root's flagship backpack product is offered as battery (Model 12B) or generator powered (Model 15D). One of the basic design goals for the Model 12B is versatility of waveforms. In addition to including the standard settings available on previous models, this model provides the following options: (1) combination waveforms, such as gated bursts, (2) sweeping of frequency, and (3) variable pulse width. The sweeping waveforms provide an output that varies in power over a selected time interval (2–10 seconds). With each activation of the anode pole switch, the power varies from an initial high power output to a final low power output.

This unit is designed to be as safe as possible to operate. The Model 12B incorporates several features that address operator safety, including a safety tilt switch, an audio power meter, a flashing light, a quick-release backpack harness, an insulated operator switch (flap switch), and high-voltage insulation from input to output.

The Model 12B can deliver high peak currents. Under short-circuit conditions, currents as high as 60 amps are possible. In some older Smith-Root units, and in some other manufacturers' units, the possibility of damage to the output devices under short-circuit conditions was reduced by the addition of impedance in the output circuit. This impedance resulted in a variable output voltage, with changes in output loading, reduced efficiency, and generation of increased heat.

From a user standpoint, the disadvantage of this approach is that it is more difficult to predict the effect of changing the settings (actual output power may vary with water conductivity, and with anode and cathode size and proximity). The Model 12B has a well-regulated output and does not suffer from this problem, as it uses a different scheme for short-circuit protection. The output voltage range has been increased to 1100 volts on the Model 12B to facilitate electrofishing in very low-conductivity water. One of the biggest advantages of the programmable output waveform is the ability to upgrade its waveforms in the future as more is learned about optimal waveforms under different conditions. Reprogramming the waveform is easy; it can be achieved by dissembling the unit and adjusting or replacing the microcontroller.

These models (12B and 15D) may have too many waveform choices for operators, based on the number of questions users ask regarding the function of the various settings. However, as we gain information on the optimum settings for different environmental conditions, species effects, and sampling objectives, this range of output selections will result in greater sampling efficiency. In the meantime, Smith-Root can provide information to users on the most appropriate or commonly used settings for different conditions.

The maximum power of Smith-Root's generator-powered backpack unit is 350 watts. If more power is required, the GPP 2.5 model can be adapted for bank-side use with an anode extension cable. The GPP is a 2500-watt unit, requiring a 100-pound generator. Extension cables for use with the GPP unit (this requires an RCB-6 junction box) and the backpack units are interchangeable. They may be used to extend the reach and reduce the weight an operator is required to carry in fast water conditions.

Electrode Configuration

Newer Smith-Root anode poles are equipped with on/off flap switches. Although some operators object to flap switches, they are safer and more reliable than push button switches, which tend to get wet inside and break more frequently. With the flap switch, the switching element (a magnetic reed switch) is buried in the red rubber switch assembly and is electrically isolated from the user. Anode poles are typically supplied in one- or two-piece models, but three-piece poles can be custom-built. The anode ring is attached with a bolt, allowing easy exchange of anode configurations, such as a standard 30 cm (11") ring, a smaller 15 cm (6") ring (for use in high-conductivity waters), a large 46 cm (18") ring (for low-conductivity waters), or a diamond-shaped array (which allows greater operator support and the ability to access small areas, but may increase the risk of fish injury). Changing anode rings is a viable way to extend the operating performance of a system. Another technique is to apply tape to regions of the anode when using it in high-conductivity waters. This technique achieves roughly the same effect as using a smaller anode ring.

Anode rings can become plated, sometimes to the point of no longer being conductive. It is therefore recommended that anodes be cleaned with an abrasive pad occasionally to remove plating.

Water conductivities lower than 50 µS/cm usually require an increase in the anode ring size or the use of very high voltage. At water conductivities higher than 1000 µS/cm, smaller rings are likely to increase performance. By varying the duty cycle on models with programmable output waveform, it is often possible to produce adequate power densities using the 30 cm (11") ring in a wide range of water conductivities.

Minimizing Fish Injury

To minimize the potential for fish injury, operators should first consider using straight DC current whenever possible. Operators using modified or pulsed DC current should first select a low output pulse rate (frequency) such as 15-30 Hz (pulses per second). Next, select a narrow pulse width setting of 1 msec. Pulse widths less than 1 msec at low frequencies tend to be ineffective. If these settings are not effective, first increase the pulse width from 1 msec to 2 msec. This doubling of pulse width will double the amount of power in the water and may be all that is necessary for good results. If not, continue to increase the pulse width to a maximum of about 6 msec. Pulse widths wider than 6 msec usually do not result in increased effectiveness. If the resulting fish response is still not satisfactory, reduce the pulse width to 1 msec, increase the voltage one step, and increase the pulse width as needed. Repeat this process, if necessary. Doubling the output voltage increases the power in the water by a factor of 4.

The objective is to keep the pulse rate and voltage as low as possible. Increasing the voltage extends the field, but also rapidly increases the amount of power placed in the water. The voltage gradient near the electrodes also increases, increasing the potential for damage to fish. The field can be extended by increasing the size of the anode. Using larger anodes reduces the voltage gradient near the anode, and thus the possibility of injury. Effective cathode size must be maintained—large with respect to the anode -- for maximum benefit. Thus, if using a standard backpack unit with a large anode, it may be necessary to alter the rat-tail cathode to proportionally increase the cathode size.. Increasing the frequency, pulse width, and duty cycle does not actually change the size of the field or peak voltage at any point in the field, although it does increase the power absorbed in the fish and the effect of this absorbed power. With a fixed duty cycle, a fish absorbs the same amount of power at a low frequency (30 Hz) and at a high frequency (120 Hz). However, there is a markedly different response in the fish, as the higher frequencies seem to have greater effect and tend to cause more damage. Using straight DC and reducing frequency (Hz) is thought to be the best way to minimize fish injury rates.

Maximum battery life and minimum possibility of injury can be achieved by using the lowest possible voltage, frequency, and pulse width. To maximize battery life and reduce the chance of injury to the fish, a starting point of 100 watts of output power is recommended. This power level is easy to identify on the Model 12B and 15D, since the audio power meter tone changes from a steady tone to a slow pulsing tone at 100 watts of output. On older models, the audio tones may not signal 100-watt output.

Also, on earlier Smith-Root backpack units, a constant duty cycle is maintained at all frequency settings. Therefore, an increase in the pulse frequency is compensated for by an internal decrease in pulse width.

The only metering available on the Model 12B is an average output current meter. Average output current changes with duty cycle, whereas peak output current remains constant for a given voltage and water conductivity. The Model 12B has an audio power meter, allowing operators to readily tell when the electrofisher is on and the appropriate voltage output.

With the sweeping waveforms provided on the Model 12B, the user can produce an output that varies from 4 msec to 0.2 msec, with the advantage of initially producing a strong effect on the edge of the field and automatically reducing the power of the field as the fish nears the anode. Reducing the pulse width (or frequency) automatically when the fish is near the anode should theoretically reduce the injury rate and increase capture efficiency.

Even a pure DC or nonpulsed DC shocking system provides some risk of injury, because the act of turning it on-and-off produces a pulse output with possible over-voltage spikes. A slow on-and-off function for the Model 12B is being developed to minimize this effect.

In the meantime, holding the anodes out of the water when turning the power on will prevent exposing fish to power-up over-spikes.

In order to minimize injury to fish, it is recommended that before conducting any sampling, electrofishing crews first adjust their equipment for optimal settings downstream from the study reach. This will prevent the tendency to adjust equipment "to whatever works" during the actual sampling.

Smith-Root Boat Fishing Units

Smith-Root boat electrofishing units do not have the same features as the Model 12B. The GPP series units have a low frequency (7–120 Hz) and high voltage capability, making them suitable for most conditions. The output is a quarter sine wave. DC filters are available for nonpulsed DC output, if necessary, becuase of limited generator capacity. Boat electrofishers tend to be less sophisticated than the backpack units, partly because of the large capacitors required for high power units and the difficulty of dealing with the high peak currents these large capacitors can supply. One should avoid the use of units with capacitors that are too small for consistent output under varying load conditions. Units that do have the required energy storage capacitors need complex circuitry for control and short-circuit current limiting, which makes them expensive and possibly less reliable. Generators are limited in the amount of peak current they can supply under short-circuit conditions. The magnetics have a certain energy storage capability and it is easy to size an output switch to handle this capability into a short circuit without problems.

Chapter 3 – Electrofishing with Coffelt Systems

by John Sharber

Coffelt offers a wide range of electrofishing systems similar to the Smith-Root equipment. Backpack shockers are considered low-power units, bank shockers are moderately powered (1000–1500 watts), and boat shockers are the most powerful (>1500 watts). The power produced by boat shockers is largely limited by the capabilities of the generator.

The original version of the bank shocker (VVP-2C) has a very simple design, consisting of a transformer to convert AC power to DC. The DC output is a simple, half-rectified waveform at roughly 60 Hz, or the generator's output. The only adjustable setting on this unit is the output voltage. Output voltage is metered in RMS, so a setting of 700 output voltage corresponds with a peak voltage close to 1200, which is required in low-conductivity waters. The VVP-2C is also capable of measuring the output wattage, input voltage, and output voltage, which provides a direct measurement of the power put into the water. Monitoring the input voltage is useful for troubleshooting.

The one major modification that has been made to this unit over the last 10 years has been a change in the output to a fast-rise-slow-decay waveform. Termed C-phase, this waveform is technically a phase control waveform. It has two advantages. First, it unloads the generator and internal circuitry during the fast rise of the waveform. A generator thus can maintain a higher voltage because nothing is being loaded. The second and more important factor is that the fast rise generates a better response from the fish than a slow rise. The literature from the neurosciences suggests that a very fast rising edge is most desirable.

The biggest difference between Coffelt backpack shockers and Smith-Root shockers is in the design philosophy. Smith-Root units offer many setting choices, whereas Coffelt units intentionally limit the number of settings. Increasing the number of settings increases the versatility, but it also adds complexity. Coffelt systems are built as simply as possible, with the philosophy that field responses in fish are too variable and unknown to make it desirable to modify waveforms extensively.

The settings available on Coffelt systems were chosen based on experience and user input. The standard output is 60 Hz, which is very effective for shocking small fish. The 120-Hz setting helps in capturing small fish, but it is also more damaging. The 120-Hz setting appears to be less effective at shocking larger fish (>30 cm), because the fish are stunned too far from the anodes to be netted effectively. The low-frequency settings are advisable for injury reduction, particularly for sensitive species such as catfish that require a low-frequency setting for effective capture.

The complex pulse system (CPS) was developed based on studies on fish injury rates. Studies conducted by Coffelt Manufacturing on trout at Lee's Ferry (Sharber et al., 1994) indicated that the injury rate for trout was 40–50%, based on x-rays, autopsies, and visual inspection, when operating at 60 Hz with water conductivity of 500 µS/cm. When the frequency was reduced to 15 pulses per second in a statewide survey in Montana, injury rates dropped to 5–10%, and most observed injuries were not as severe. The sampling however, was not as efficient and required more time to capture the same number of fish. Based on this information, Coffelt developed a technique to deliver the pulses in packets, CPS. The primary cause of injury is frequency, not voltage.

Coffelt believes that fish injury occurs at low levels of stimulation, and may occur whenever enough power is supplied to stun fish. At the first sensation of power, a fish may effectively swim out of the field unharmed. If it continues to swim toward the anode, the fish may begin to exhibit signs of a reaction similar to an epileptic seizure, which may or may not be accompanied by a myotonic jerk. The myotonic jerk occurs for reasons unknown and is not reproducible, but this phenomenon is the primary cause for spinal injuries associated with electric shock. The myotonic jerk usually occurs in the very low levels of the epileptic seizure. The forced swimming occurs at a higher level, although myotonic jerks can also occur in this range.

Coffelt and Smith-Root systems differ in their approach to pulse width. Pulse width, or duty cycle, is usually referred to as a percentage. On newer equipment, the pulse width is not defined; it is variable according to the loading. On Coffelt backpack units, which are limited by the ability to power them, (as all backpack units are), the pulse width starts out at 3–5 msec, independent of the frequency. If the voltage is set at a higher level than the generator can supply, the circuits compensate by automatically decreasing the pulse width to maintain output voltage. Peak voltage is the most important parameter. Coffelt believes that pulse width is less important, since nerve cells fire only once, and no more changes occur until the cell's chemistry returns to pre-firing conditions. Applying voltage with a long pulse width to a cell can inhibit the ability of the cell to reset itself. Pulse width should therefore be kept as short as possible. Coffelt units have a range from 1.5 to 6 msec. Pulse widths longer than 6 msec can alter the cell response to the point of reduced electrofishing efficiency. Very narrow spikes in power, however, may be ineffective at stimulating nerve cells, which can be addressed by grouping the individual pulses into packets, as is accomplished with Coffelt's CPS technology.

Electrode Configuration

Anode design has the goal of producing current flow in the water. All electrodes are less than 100% efficient because there is some resistance of the electrode at the physical interface between the electrode and the water. From a physical standpoint, a sphere is the ideal electrode for a given size because it has the least amount of surface resistance. Spheres could be made of mesh instead of solid steel and produce the same effect, but it is unlikely that drag would be substantially reduced. The other extreme is a single cable, which is the worst electrode imaginable.

The Wisconsin ring was developed as a method to simulate a sphere but decrease the weight and drag (Novotny and Priegel, 1974). Coffelt has both sphere and Wisconsin ring electrodes. In a comparison of the 2 configurations on 2 boats fishing side by side in 11 lakes (conductivity range of 20–8000 µS/cm), a 30 cm (12") sphere and a Wisconsin ring (71 cm (28") diameter, with 20 droppers, each 30 cm long) provided nearly identical results. The decision about which anode to use depends on the ability to sweep the electrode through the water.

Wisconsin rings were developed with as many droppers as possible. The complex interactions among the fields produced by the individual anodes result in a field similar to that produced by a sphere—maintaining the three-dimensional properties of a sphere's field and allowing penetration to similar depths. The number of droppers in the water is important, not only in terms of the surface area but also in terms of the configuration. The depth of an electric field is not usually evaluated, because it is difficult to do, requiring a swivel head on a voltage gradient probe to locate the peak gradient.

The umbrella cable array manufactured by Smith-Root is effectively a Wisconsin ring without the ring (which serves no functional purpose except as a place to hang the droppers). It can hold as many as 18 droppers. An advantage of the umbrella array is that it collapses and is less likely than the Wisconsin ring to get caught on in-stream vegetation. Also, a Wisconsin ring on a boat unit can shift or flip if it is mounted too close to the water's surface.

The general rule with all electrodes is the bigger, the better. Coffelt droppers are made from 2-inch hollow steel tubing. On rings with 20 droppers, ¼-inch hollow tubing is used, which may increase the resistivity of the electrode by 10–15%. The number of droppers is more important. The Wisconsin ring is such a complex, geometric object that small changes do not affect it; however, an effect might be observable with ⅛-inch cable. The only way to test the difference would be to build two systems and test them side by side, since the complexity of fields generated from a Wisconsin ring prohibits calculating these differences.

The ultimate decision about which anode configuration to use depends on the physical conditions in which electrofishing is conducted. If there are no limitations, then the best anode would be an 18-inch or a 20-inch sphere. A large ring is almost as good as a sphere. The option selected may depend on the ease with which it can be maneuvered in habitats of interest. The same tradeoffs apply for backpack shocking; although 18-inch rings are more effective, they are not practical in most shallow streams.

Kolz (1993) reviewed electrical fields produced by different electrofishing configurations, including a characterization of spheres (2 sizes), Wisconsin rings (4 sizes), horizontal loops, and umbrella arrays using various numbers and sizes of rods. The test electrode configuration that produced the greatest voltage gradient and thus the shortest extent of electrical field was a 36-cm loop, while a 45.7 cm vertical plate produced the lowest voltage gradient and farthest field. Thus, the choice of electrode configuration depends on a variety of both electrical and biological factors, there is no electrode that is ideal for all conditions.

Fishing effectively in deep water can be approached in several different ways. The greatest netting of fish occurs when fish are in a state of narcosis, which may not occur near the anode. One technique to bring fish toward the surface and closer to the anodes is to decrease the voltage, which must be done within the context of the given electrofishing protocol. If the goal is to shock fish at greater depths, then extending the electrodes deeper into the water and using longer handled nets may improve capture efficiencies, since fish are attracted to the geometric center of the field or to the point of greatest field intensity. A third technique is to increase the size of the ring or sphere, which will increase the spatial extent of the area of greatest field intensity. Anodes can be used individually or in pairs. A single ring produces a field with a greater depth than two rings. Two smaller rings will extend the field laterally, but will not increase the depth of the effective field.

Species Sensitivity

Benthic fish can be very difficult to capture efficiently. Fish that burrow into clay receive protection from the conductivity of the clay. The high surface area of clays is covered with salt-saturated water, which conducts electricity very well, and can short out the electric current in the immediate vicinity of the fish.

Fish without swim bladders, such as catfish, are often not attracted to the anodes. Using a very low frequency can be helpful. If 60-Hz power is used, then sensitive fish (e.g., catfish) enter tetany far from the anodes and are not seen by the netter. At 10–15 Hz, electrotaxy is induced, which can lead fish to the surface. Another technique that has been used in areas with abundant catfish is to shock and then stop and wait for the stunned fish to surface.

Sculpins, which tend to dive into sand and gravel in response to an electric stimulus, can be difficult to capture. If a fish aligns itself from head to tail along a line of equal potential, it can swim following this line, which may lead to the bottom; this explains why some fish can appear to have their noses buried in the substrate. A "hoovering" manuever is often effective in brining these fish to the surface.

Lampreys and Pacific giant salamanders react in a peculiar way to an electrical field; they tend to stun easily and recover quickly. Other species do not stun as easily and recover much more slowly.

Troubleshooting

The first action, when an electrofishing system stops working, is to check the cords, booms, and electrodes. Look for loose connections. An ohmmeter or multimeter is very useful for checking external circuitry. Check each segment of the circuit for continuity, and then join the pieces to check for continuity to the tips of the anodes. Most voltmeters read RMS voltage, not the peak voltage, thus it is a good idea to measure the output from the machine. Although the numbers are not directly interpretable, it is a good test of standardization between sampling times, and could be used to develop a calibration curve.

The internal circuitry is too sophisticated to permit extensive troubleshooting in the field. Most repairs can be made by the manufacturer with a 1–3 week turnaround, depending on the season. Faster turnaround times are possible, but usually at additional cost.

Equipment Care

An electrofishing unit is a sensitive electronic instrument. It should not be thrown in the back of a pickup on a bumpy road. Most units are made to be water resistant. If a unit accidentally falls into the water while it is on, the only component that might be significantly damaged is the meter. It has a jewel movement that will fail if too much grit gets into it. Drying out the unit well before turning it on again should revive it. A hair dryer could be used for this purpose. Rubbing alcohol will also help dry out components. Although Smith-Root shockers have gaskets and Coffelt units do not, neither will be damaged by rain. Dust is rarely a problem.

Chapter 4 – Interpretation of Electrofishing Data

by Peter Bayley

Careful and consistent interpretation of data from electrofishing efforts is a critical component of the use of electrofishing for both monitoring and research purposes. However, interpretation of these data can be far more complex than for many other research methods due to the variations in catchability among gear types, species, habitats and environmental conditions. There is an entire body of literature and statitsical methods for population estimation, which is beyond the scope of this document. This chapter, then, focuses on the importance of considering these sources of variability, with particular emphasis on relative capture efficiencies of fish, based on species and age).

Catchability is typically normalized for level of effort, as catch per unit effort (CPUE). Assuming that CPUE is proportional to the abundance and numbers of fish in a given area, then CPUE is equal to a constant times the number of fish per unit area. The constant is termed catchability, and is conditional on a given sampling procedure. CPUE = (total fish caught/area sampled) × q where q = catchability or probability of capture. Recent efforts in fisheries modeling have more realistically treated catchability as a random variable, based on a mathematical function, rather than a constant. This practice, however, ignores the fact that we know that catchability varies somewhat predictably with regard to species, habitat and gear type.

Identifying Project Goals and Capture Techniques

The first and most important action, with respect to electrofishing issues, is to identify the project goals. There is a hierarchy of possible goals, ranging from general assessments of fish species presence to rigorous estimates of populations and biomass. The level of effort required follows a similar hierarchy.

Suppose the goal of a study is to determine age-specific mortality rates of a population of trout. Approaching this objective using electrofishing would require knowing the relative catchability (size "selectivity") of trout of different size (and therefore age) classes in order to produce an unbiased length/frequency histogram. Using this information, plus back-calculated length-at-ages data, it would be possible to estimate age-specific mortality rates. Knowing the actual catchabilities is not required.

In electrofishing, often the goal of a study is to determine community structure, (e.g., number of individuals by species in a given habitat). The species of interest often have different catchabilities. If the goal is to determine species presence/absence information, the impact of varying catchabilities is very important. Probability of capture is essential for making inferences about species presence and richness. When this information is not provided, then the capture data should be interpreted only as presence data, as in collection surveys. Collection surveys and museum collections provide information about what fish species have been caught in various locations, but lack of capture cannot be used to infer that a species was not present, unless information is provided about the catchability of this species using the specified gear and sampling protocol. There is an important distinction between (1) presence data alone and (2) presence/absence data, by which one can presume to infer the absence of a fish species.

Determining probability of capture is straightforward, if the total number of fish in an area and the rate of capture are known. For example, if there are 10 fish in an area and 2 are caught on average, then the efficiency of capture is 20%, implying that each individual fish has a probability of 0.2 of capture, given that particular standardized method of capture. If the effort is doubled, then twice as many fish should be caught. Continuing this logic, if the density of fish is doubled in a given area for a given unit of effort, the catch should double. The basic assumption is that catch per unit effort (CPUE) is directly proportional to fish density when habitat is held constant. Density is important; unless an area is defined in which the fish are distributed, catch per effort is not very meaningful. This concept also applies to the use of passive sampling gear (e.g., gill nets), where some average fish density is implied, even though individual fish may come from varying distances to be caught.

Sampling Strategies

Unless mark-recapture techniques are employed, electrofishing programs must address the following issues relative to catchability: (1) use of a consistent sampling strategy that ensures a predictable catchability for the a given gear type under given conditions, and (2) predicting changes in catchability under different conditions that cannot be controlled by the sampling method. While the first issue primarily concerns the capabilities of the gear and crew (sampling method), the second issue concerns appropriate interpretation of catch data.

The ability to determine how to predict catchability under variable conditions can be improved using efforts to standardize collection techniques and data. When the area sampled is not fixed, standardization of unit effort becomes critical. Effort for a given set of gear can be conceived of either in terms of time or space. Time standardization, particularly in flowing streams, has the disadvantage of being independent of area sampled and can vary widely depending on the complexity or heterogeneity of habitat present. Consider a sampling scheme based on time. In one year, fishing begins at point A and ends at point B. The next year, fishing is conducted for the same length of time, but the endpoint is at another location, point C, resulting in a different area being fished. The ratio in sampled area may not be the same as the ratio in time because there is a tendency in electrofishing to proceed more slowly when fish are abundant, and more quickly through areas where few fish are caught. There is also a tendency to spend more time in habitats perceived to be good, even if fish are not encountered. These are reasonable protocols for experienced crews. However, if the habitat between points B and C differs from that between points A and B, the samples between the two years are not directly comparable.

Once the effort has been defined, there are several statistical approaches to correct for variable levels of effort. It may be desirable not to sample the same distance in all cases. For example, if the sampling protocol includes stratifying the sampling effort according to habitat type, then the natural distribution of habitat types may not be according to a fixed length of stream or a fixed length of shoreline along a lake. Even when standardized protocols are adopted, variation occurs in the field. The issue is how to sort out the major sources of variation from random or less significant factors. Even under ideal conditions with respect to electrical gear and crew, there will still be variability associated with water depth, turbidities, volume flows, and effects of physical impediments to the fishing process. In addition to these factors, there is also variability associated with the response variable, such as species and size of fish.

If a standardized effort protocol is not employed, then catchability is impossible to predict. If a standardized effort protocol is adopted, then the variability associated with gear and operators can be eliminated, but the catchability still is applicable only to defined environmental conditions.

Estimates of Capture Efficiency

The importance of catchability, and limitations in the interpretation of historical data, can be illustrated through two 3-year gear calibration programs in streams and lakes funded by U.S. Fish and Wildlife in the Midwest (Bayley and Dowling, 1990). Several primary gear types were used to capture fish within areas confined by block nets in streams and lakes and also within whole lakes (conductivity = 250–1000μS/cm), including boat shockers (3-phase AC unit), backpack shockers, and an electric seine. The electric seine was powered by a 125-volt generator with drop electrodes. The results of this study are summarized below.

This sampling was followed by limited application of a more efficient secondary method (rotenone) to estimate the number of vulnerable fish species. Since rotenone is not 100% efficient, mark/recapture techniques were used prior to rotenone sampling. The rotenone application has to be performed by experienced personnel, and was calibrated based on the volume flow rate as calculated using a Marsh McBirney velocity meter to estimate discharge rate. This procedure also permitted an accurate calculation of the amount of potassium permanganate needed to detoxify downstream. The only restriction was to avoid areas where endangered species were present. The systems were extremely productive and water temperatures (>17°C) were such that detoxification occurred rapidly. The secondary method was used to calculate the number of fish vulnerable by size and by species on the basis of the mark/recapture efficiency. The number of vulnerable fish as determined by the secondary method was compared to the catch using the primary gear to estimate catchability or capture efficiency. Catchability can be estimated just by introducing marked fish, but smaller quantities of fish can be used and the previous experience of the fish may alter their catchability.

The results showed that probability of capture was dependent on fish length for centrarchids, top minnows, darters, and catfish. In streams, water velocity was also important. Using the data from the rotenone application, the relationships between capture efficiencies and water visibility, turbidity effect, and water temperature were investigated. Catchability was positively correlated with fish size for boat electrofishing within areas contained by block nets. This size selectivity was highly evident in lakes, where catchability decreased for larger fish. Turbidity was important. The highest catchability occurred in moderately turbid conditions. At low turbidity, the fish could see the boat and moved out of the area. At high turbidity, catchability was low because of the decreased visibility for the netter.

For the backpack electrofisher in streams, catchability was positively correlated with fish length, physical impediments (including deep water), and water temperature. Conductivity did not have a consistent relationship with catchability. A relationship might have been more obvious if the range of conductivity included waters of lower conductivity (20–70µS/cm).

For the electric seine, catchability was positively correlated with fish length. Catchability increased with proportion of habitat as riffles. Lower efficiencies were obtained using a 50-foot seine compared to the standard 30-foot seine in streams of widths similar to the seine lengths. This difference would probably be reversed in wider streams. Catchability decreased as the product of stream width and depth increased. Species differences were important among some groups. For example, with the electric seine, catchability was much lower for catfish than for minnows. Therefore, more samples would be required for catfish than for minnows to accurately predict population parameters beyond presence/absence.

Catchability can vary considerably among both habitats and sampling methods, particularly with backpack shockers. In the high-conductivity range (>400 µS/cm), the power available is limiting. Also, schooling fish, such as minnows, tend to swim around the field. One technique to increase the catch of schooling fish is to have the crew keep an eye out for schools of fish swimming outside the field, and then placing the electrode directly in their midst. For centrarchids and other fish that seek holes in the banks, backpack shockers and electric seines have similarly low catchabilities in very small streams.

In lakes, Bayley and Downing (1990) found that the length of shoreline sampled did not significantly affect efficiency. Catchability decreased as depth and/or surface macrophyte cover increased. Although improving efficiency is a worthwhile goal in electrofishing, it is better to use a less efficient system with reliable estimates of the probability of captures than to constantly improve and change methods with no knowledge of their capture efficiencies. New techniques should be adopted only after calibration of relative capture efficienies have been well-established.

Interpreting Presence/Absence Data

The interpretation of presence/absence data for determining species richness provides an example of the importance of knowing catchability. Suppose the probability of capture for a species is 0.5; the chances of catching an individual of this species in any given sampling effort is 50%. If two individuals are present, the chance of not catching either of them is 0.25 (0.5 x 0.5), and the chance of capturing a fish of this species is 0.75 (1 x 0.25). For a case in which five individuals are present, the chance of not capturing any individuals is 0.03, and the chance of capturing at least one is 0.97. This example can be extended to multiple species to determine species richness. For a given number of species, the chance of catching a single sample with all the species represented would be the product of all the individual probabilities of capture.

Consider two sites (A and B), each with populations of the same six species— three minnow species and three sculpin species. Assume that the catchability values for minnows and sculpins are 0.5 and 0.1, respectively, under the conditions encountered. At Site A, there are 10 of each minnow species and 5 of each sculpin species, for a total of 45 fish. At site B, there are 5 of each minnow species and 10 of each sculpin species, also a total of 45 fish. Both sites have fairly high species evenness, the same total number of individuals, and similar habitats, such that catchabilities for minnows or sculpins do not differ between the sites. The probability of encountering all six species is 0.068 (6.8%) for site A and 0.251 (25%) for site B, about a fourfold difference. This hypothetical example demonstrates that catchabilities among species and the populations of those species determine the estimates of species richness. Although the influence of these factors decreases as population size increases (increasing the chance of encountering an individual of that species), almost all sites contain some species with low abundances. This example could easily be extended to more complex fish assemblages to determine the probabilities of accurately estimating richness and relative abundance, with functions estimating the likelihood of sampling different species richness.

In addition to varying species and sizes, species catchabilities can differ with stream conditions and habitat types. Unfortunately, very little information is available on the catchabilities of most species under specified conditions. However, using the best approximate catchabilities available in the literature is more advisable than ignoring the issue of variable probability of capture. There is an urgent need to develop a better understanding of species catchabilities under different conditions.

Chapter 5 – The U.S. EPA's Environmental Monitoring and Assessment Program (EMAP)

by Robert Hughes

The U.S. EPA's Environmental Monitoring and Assessment Program (EMAP) is designed to collect information on the condition of sites across a large spatial scale (river basins to nations). The goal is to get a pulse of the fish assemblage through time, not to assess changes in processes over time. EMAP relies on electrofishing as the primary capture technique. EMAP has developed several techniques to control and record variability among sites and sampling times to maximize the ability to interpret data for the purpose of gaining a snapshot of fish assemblages through time and across an enormous spatial scale.

This chapter describes the scientific basis for EMAP's current protocol. The main point is that the effective sampling area or distance, as well as gear performance, is critical for data quality and interpretation. Pilot studies on gear, sampling period (season, time of day), and area sampled are essential before initiating a major electrofishing survey.

The EMAP protocol is based on research in which the electrofishing catch was recorded for successive units of small to mid-sized wadeable streams. The research demonstrated that collection of all species present in the area sampled requires electrofishing a length of stream equal to 25–80 wetted channel widths. In mid-sized streams, a reach length of 40 channel widths is sufficient to capture all species but those accounting for <1% of the total catch. In small headwater streams, around 1–2 m wide, new species typically were not encountered after the sampling reach equaled 19–75 channel widths (Reynolds et al., in preparation). Similar results have been reported for streams in Wisconsin (Lyons, 1992), Illinois (Angermeier and Karr, 1986), Virginia (Angermeier and Smogor, 1995), and South Carolina (Paller, 1995).

The EMAP sample reach for wadeable streams, then, is defined as 40 wetted channel widths, with a minimum of 150 m (McCormick and Hughes, 1997). Pilot studies in 1994 (Willamette Valley) and 1997 (Oregon-wide) on nonwadeable rivers (Figure 5), indicate that 30–100 channel widths are necessary to collect all but the rarest species when electrofishing a single near-shore transect. A maximum reach length of 2000 m is recommended, but the 1997 data analyses are only preliminary.

Results from the EMAP method were compared with those from dive electrofishing used in the Long Term Ecological Research Program (LTER) at the H.J. Andrews Research Station to illustrate annual variability in abundance for two methods of varying labor intensity (Figure 6). The LTER dive electrofishing protocol is for two crew members in full drysuits dive underwater with anodes and small hand nets. This method is labor intensive, typically involving 5 or more people for a total of 200 person hours per reach. Based on mark/recapture studies, efficiencies of dive electrofishing are 70–80% for larger fish, and slightly lower for smaller individuals. The EMAP method (9 person hours) requires about 5% of the time and produces about 5% of the fish, compared to the LTER method in the same reach. In other words, catch per unit effort is comparable between the two; relative abundances of the various species in the reach were also similar. This means that the EMAP protocol provides a sufficient index of the fish assemblage, except in the case of extremely rare species.

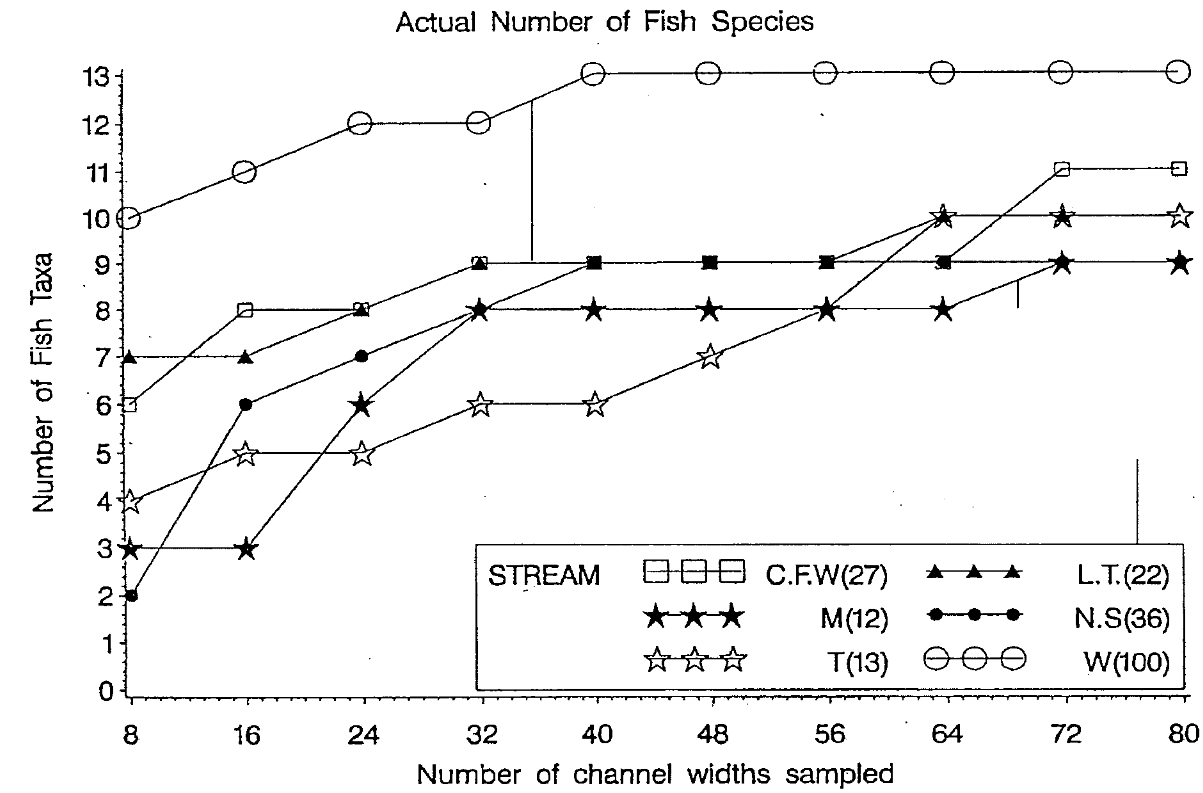

Figure 5. Fish species richness as a function of sampling effort for six nonwadeable rivers. Effort is measured by the number of wetted channel widths electrofished; numbers in parentheses for the six rivers are mean channel widths. Note that 90% of the species were collected in 80 channel widths (1152 m and 3200 m for NS and W, respectively). Other rivers, such as M and CFW did not yield 90% of the species until 64 channel widths were sampled (768 m and 1728 m, respectively).

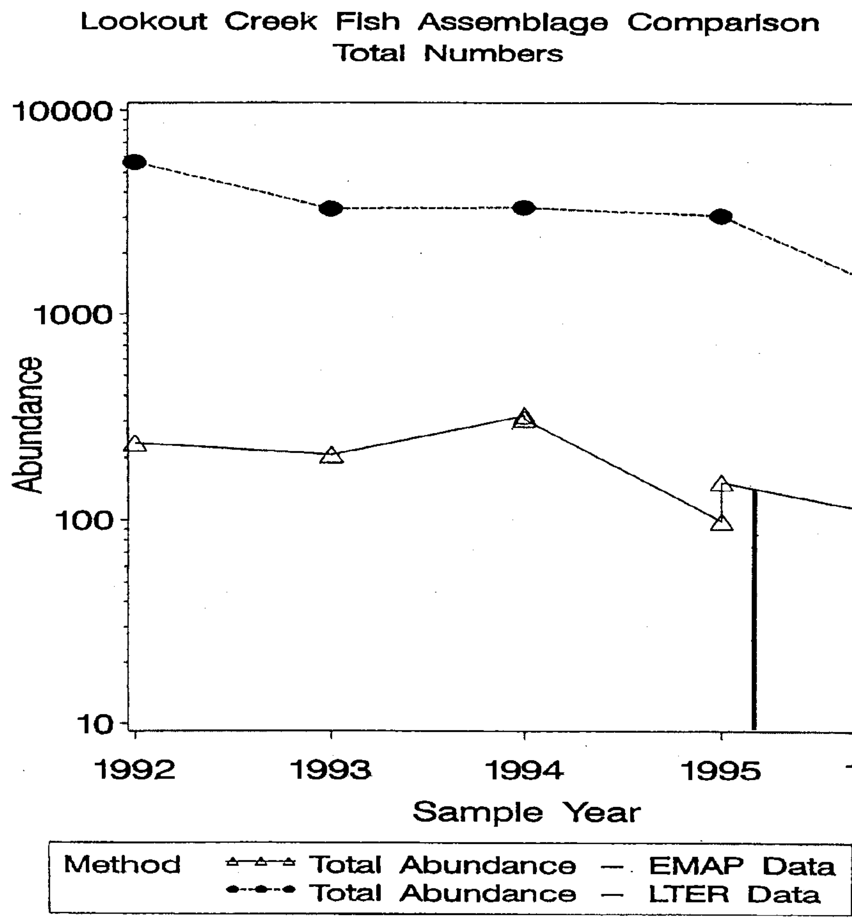

Figure 6. Fish abundance as a function of effort using two electrofishing methods. The LTER method of dive electrofishing requires 200 person hours, compared to the EMAP method, which requires 9 person hours. Catch per unit efforts are similar with the two methods. Note that EMAP repeat samples in 1994 and 1995 yielded comparable numbers of fish.

Fish data from the Willamette Valley streams were transformed using a modification of Karr's index of biotic integrity (IBI), which collapses information on individual species and their abundances to a single number (Hughes et al., in press). IBI values were fairly consistent through time (1993 and 1996). However, larger differences were detectable among sites than among sampling visits during a summer season (Figure 7). These results indicate that the EMAP electrofishing protocol provides a precise (repeatable) sample, even among different months, years, and crews. In other words, sampling variances were markedly less than among-stream variance.

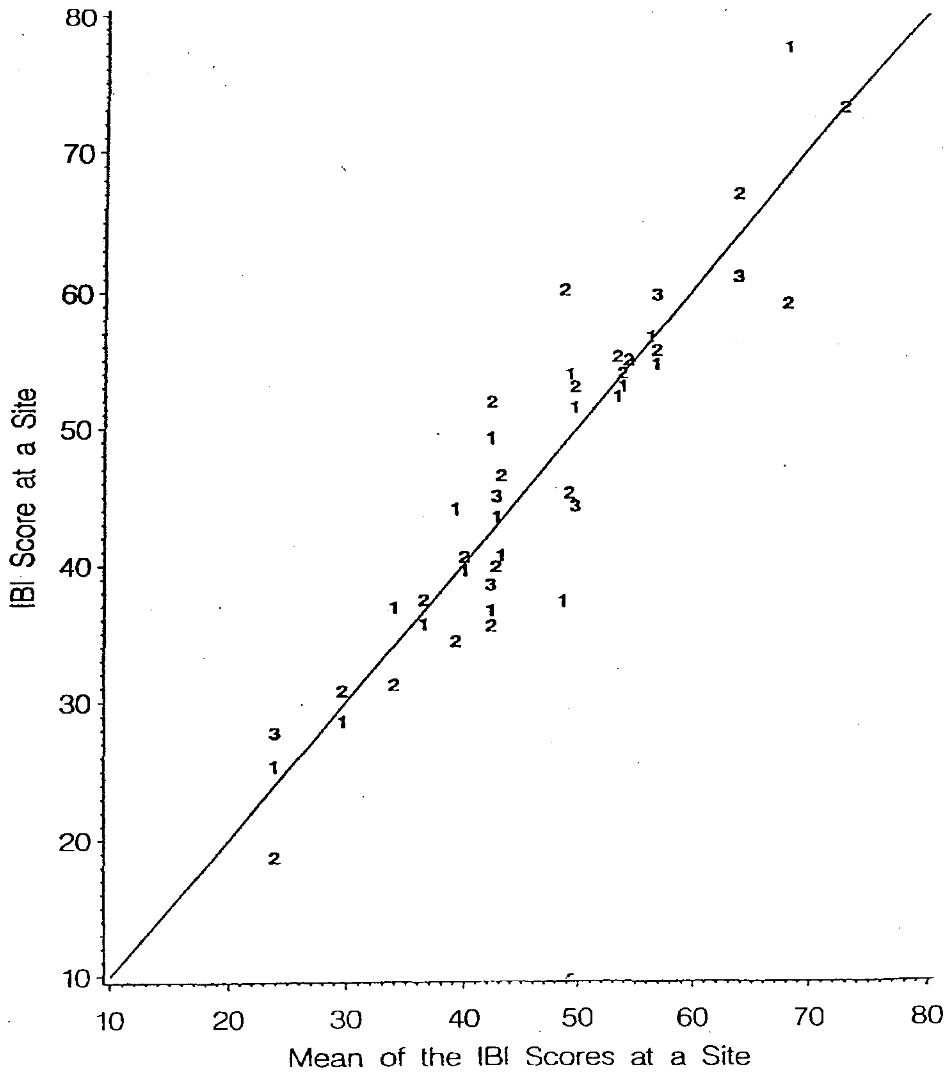

Figure 7. IBI precision as indicated by monthly sampling visits at the same site in a summer. Numbers represent months sampled (1 = June, 2 = July, 3 = August) and their vertical positions indicate the IBI score on that visit versus the mean of all visits to that site. Note distribution within a sampling event spans a wide range of IBI scores.

Chapter 6 – Experiences from the field: alcove sampling on the Willamette River, OR

by Chip Andrus

The electrofishing workshop preceded a three-year effort by EPA to quantify fish assemblages in main-channel and off-channel portions of the upper Willamette River, and to evaluate factors that influence fish abundance, size class, species mix, and outer anomalies. In the sampling design stage of this project, we confronted many issues in which we were constrained by equipment and field conditions. The following comments address what we learned in the sampling design and implementation of electrofishing techniques in the main-channel and off-channel habitats of a large river.

Our initial focus was to evaluate fish assemblages within a type of off-channel feature called alcoves. These riverine features have a downstream connection to the main channel during the summer but not an upstream connection, although some water may enter the alcove below the surface. Sampling alcoves is accompanied by several constraints. Landowner property extends to the summer low-flow water level so sampling must be boat-based unless landowner access approval is granted. In the Willamette River, the substrate in the alcoves can be extremely mucky, limiting the ability to walk in the water and see fish if the substrate is disturbed. The riparian banks are often very heavily vegetated, making shore access difficult. Depths vary from 0.2 - 3.0 m, and the turbidity of the water can limit vertical visibility. Water conductivity for most Willamette River alcoves is 50–70 µS/cm, but can reach 100–300 µS/cm in certain alcoves. Conductivity also may vary within alcoves due to variations in groundwater connectivity and hyporeic flow. Macrophyte beds can be very dense. Pilot work indicated that fish distribution is very clumped, suggesting the need for an appropriate stratification system if cover features are to be sampled individually.

Initial attempts to catch fish within alcoves were dismal. Catches after 15 minutes of sampling during the day were seldom more than 10 fish. We switched to night sampling, which has been shown to yield a higher number of species and greater abundance of fish than daytime sampling (Sanders 1992; Dumont and Dennis 1997). The difference was astounding; we now faced the problem of where to put all the fish. Although we were confident that night sampling represented a superior method, we were unsure whether the increased catch was attributable to nightly fish migration from the main channel into alcoves or simply that nighttime conditions are more favorable for fish capture by electrofishing. Or, maybe it was both.

We addressed this issue by changing our sampling protocol so that daytime and nighttime fish assemblages would both be evaluated using nighttime electrofishing techniques. To evaluate daytime assemblages, we set block nets at alcove entrances during the late afternoon, thereby trapping the fish using the alcove during the daytime within the alcove. We then sampled the alcove beginning at midnight. To evaluate nighttime fish assemblages, we set block nets at midnight, thereby trapping the nighttime fish within the alcove. Again, sampling began shortly after midnight. A coin toss determined whether the daytime assemblage or the nighttime assemblage was sampled first. Several days separated the first sampling period from the second.

We found that abundant catches of fish at night were due both to fish migrating into the alcove at night and to fish being more vulnerable to electrofishing at night. A migration of larger fish (201-550 mm) from the main channel into alcoves occurs at night with the relative abundance of nighttime fish averaging about 5 times greater than of daytime fish. By contrast, the overall relative abundance of smaller fish (60-200 mm) did not differ significantly between nighttime and daytime fish assemblages. However, individual species of smaller fish tended to move into the main channel at night while other species tended to move into alcoves.

We also tested daytime versus nighttime electrofishing in main channel reaches of the river with the same results. Fewer fish were caught during the day than at night. The differences were greatest in shallower water where attacks by osprey and other predators are more likely to occur during the day. It appears that under the cover of darkness the fish moved freely in shallow portions of the river and did not spook much even when illuminated by our boat lights.

The conductivity of the alcoves and main channel reaches ranged from 50-140 *u*S/cm and so we pondered how we would adjust the electrofishing unit so that it would deliver same power regardless of water conductivity. We mapped the voltage gradient around our two anodes (6 stainless steel dropper cables arranged in a 92-cm-diameter circle) and the boat. The aluminum boat was wired to be the cathode. The voltage gradient field was highly irregular. As expected, voltage decreased with increasing distance from the anodes, but then increased again near the bow of the boat. Furthermore, strong voltage gradients existed along the sides of the boat and peaked at the stern. Indeed, the behavior of fish we sampled exhibited irregular patterns. Fish often orientated themselves at right angles to the boat and bumped up against it instead of congregating close to the anode where voltage gradients were highest. The behavior of fish (especially the abundant largescale suckers) did not follow expected relationships between shocking intensity and distance from the anode. Some suckers were pulled to the anode at distances of up to 10 meters while other suckers originating near the anode would swim free with apparent ease. This left us confused as to how voltage changes for varying water conductivity would influence the voltage gradient map. We therefore chose a single voltage setting for the field season.

The single voltage turned out to not be a problem, as water conductivity had no discernable effect on catches among sites for the range of conductivity values we encountered (using a consistent voltage output). For example, combined catches of smaller largemouth sucker, mountain sucker, and chiselmouth (referred to as scrapers) within alcoves were correlated positively with the abundance of macrophytes and whether or not the surrounding area was vegetated (adjusted squared multiple $R = 0.63$). The residuals from a multi-variable linear regression equation including these two factors were not correlated with water conductivity, suggesting that, after the density of vegetation and macrophytes was accounted for, an insignificant portion of the variance in catch was explained by water conductivity (Figure 8). Likewise, residuals from a multi-variable linear regression equation with large scrapers as the dependent variable and the abundance of logs, total dissolved nitrogen, and chlorophyll *a* (all positively correlated) as dependent variables (adjusted squared multiple R = 0.84) were not correlated to conductivity (Figure 8). Apparently, electrofishing efficiency was relatively constant throughout the range of conductivities we encountered. Alternatively, variability due to inconsistent electrofishing efficiency was minor compared with other sources of variability.

Netter prowess was one of the greatest sources of catch variability we encountered. Some people simply have a greater ability to predict the behavior of fish and catch them efficiently. This becomes most evident when dozens of fish suddenly appear in front of the anodes. During most of our sampling periods we used two netters. It was not uncommon to have one netter catch 2 to 3 times as many fish as the other. Using the same netters throughout a sampling period or among sampling periods was important when evaluating fish assemblages throughout a study area or when evaluating seasonal or year-to-year variability. Similarly, Hardin and Connor (1992) reported significant and inconsistent differences in catch efficiency among electrofishing crews in terms of overall and size-class catches for two lakes in central Florida.

When we began sampling fish the following spring we had great difficulty catching fish using the previous summer's settings. The conductivity of the water had dropped to about 35 *u*S/cm (by spring). Increasing voltage did not increase our ability to catch fish, but increasing pulse width had a strong influence. The pulse width is the length of time that the peak amperage is applied to the water. Sampling efficiency could be raised to summer levels simply by increasing the band width. Now, we had another problem; vulnerable fish, such as mountain whitefish, were suffering high levels of mortality, especially when they brushed up against the anode cables. We substituted the cable array with a spherical anode constructed from two 10-inch-diameter stainless colanders. The colanders were bolted together to form a sphere and the sphere was suspended into the water from a stainless steel cable. The mortality problem disappeared and the sphere did not hang up on underwater snags and branches any more than the cable array. An added benefit of the sphere was that fish were brought closer to the surface. The water was sometimes murky in the spring, so fish drawn close to the surface were easier to catch.

While preferable for scientific collection purposes, nighttime sampling created safety and logistic problems. Even with an array of automobile headlights shining in the water and two 1.2 million candlepower lamps set up to illuminate the river at longer distances, navigation at night was a major concern. Obstacles such as logs or gravel bars could be easily discerned, but identifying shallow water was a problem. Entering fast and shallow water unexpectedly occasionally resulted in a clogged jet motor and difficulty in rowing to shore, often with limited ability to see downstream hazards, such as log jams. We found that being at a site during the day just prior to sampling allowed us memorize hazards. Also, it was nearly impossible to measure distances in the dark using an electronic rangefinder, so reaches were measured and marked during the day with reflectors and light sticks. These precautions enabled us to conduct our research safely.

Clearly, the approaches that we chose to adopt will not be appropriate for all electrofishing efforts, but we hope the process of problem-solving and, perhaps, some of the specific techniques will be helpful to other fisheries biologists facing similar dilemmas.

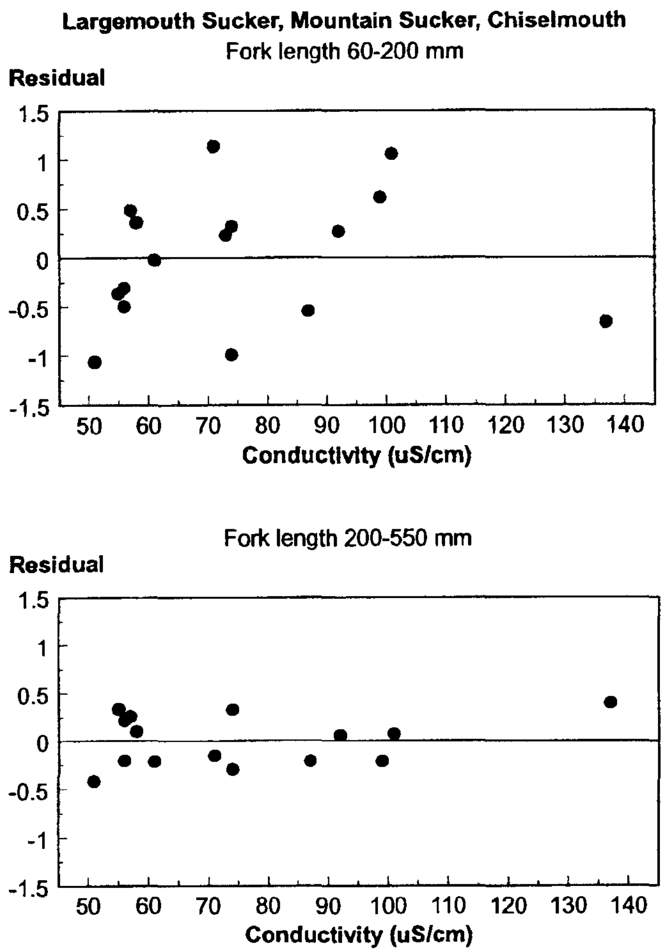

Figure 8. The relationship between catch of select fish species and water conductivity, after accounting for density of vegetation and macrophytes. Plotted as residuals of linear regression analysis vs. conductivity.

Chapter 7 – Discussion and Summary

by Susan Allen-Gil

After two days of intensive classroom lectures, and two days of gear examination and sampling protocol exercises on the Willamette River, the group collectively addressed several broad questions regarding the practice of electrofishing. These questions were related to concerns about avoiding injury to fish, weather-related safety considerations, reproducibility of results (science vs. art), acceptable and optimal sampling strategies, parameters to be reported in the literature, and the future of electrofishing.

Does electrofishing inherently cause fish injury?

Electrofishing clearly can injure and kill fish. The type and severity of injury result from the combined effects of the properties of electricity (current and voltage) and the individual susceptibility of the fish species and life stage (Holmes et al., 1990; Lamarque, 1990; Sharber and Carothers, 1990). The incidence of different types of effects (ranging from sublethal injury to population-level impacts) are inversely proportional to the severity of impact; temporary injuries are most common and population level effects are rare (Holmes et al., 1990). The debate in fisheries regarding the appropriateness of continued electrofishing practice in light of fish injury and mortality is as much driven by the public perception of the activity by natural resource managers as by the limited perspective on the broad-scale effects (Schill and Beland, 1995).

The three types of injuries encountered most often as a result of electrofishing are hemorrhaging, spinal injury, and death. Hemorrhaging or bruising near the skin surface, (which is often called branding), is the most common evidence of fish injury. It is most prevalent among fish with fine scale structure, such as salmonids. Hemorrhaging or bruising is the result of destruction of blood vessel walls below the skin surface. The reason electrofishing causes hemorrhaging is unknown, but it does appear that most injuries in this class are temporary (Schill, pers. com.)

Spinal injury is a result of compression of the vertebrae, and is believed to be caused by simultaneous bilateral contractions of the skeletal muscle. Spinal injuries can result from natural causes; the occurence of vertebral compression and hemorrhaging at the same location within a fish is indicative of electrofishing-induced injury (Sharber and Carothers, 1988). Mortality induced by electrofishing can result from hemorrhaging of the dorsal aorta (Bardygula-Nonn et al., 1995), or from severe spinal injury (Holmes et al., 1990). Performing a limited number of field autopsies to detect internal hemorrhaging and spinal injuries can provide useful information on injury rates for specific electrofishing equipment and practices.

The frequency and severity of injuries and mortalities depend on the properties of the electricity and the fish species and life stage. Sharber et al. (1994) reported that spinal injuries increase with rising pulse frequency, and that injury rates can be reduced through the use of complex pulse patterns in rainbow trout. Holmes et al. (1990) found a greater response for rainbow trout (none, twitch, escape, or stun) with increasing voltage, voltage gradient, and power density. In a study of the effect of varying electrofishing configurations on the response of goldfish, Kolz and Reynolds (1989) found that the magnitude of power density transferred to the fish determined its electroshock response. Egg survival of cutthroat trout was affected more by voltage level than by waveform or pulse width (Dwyer and Erdahl, 1995). The fact that injury and mortality rates are specific to the gear and the applied settings makes it difficult to compare results from different studies.

Species and life stages respond differently to electrical power in the water. Although research has been conducted only on a small fraction of North American fish species, there is evidence that adult rainbow trout have a higher susceptibility to injury and mortality than many other species. Sharber and Carothers (1988) reported spinal injury rates between 44% and 67% in rainbow trout. This was confirmed for large rainbow trout captured by electrofishing in the Kenai River, Alaska, that showed a 14% mortality rate and a 41% injury rate (Holmes et al., 1990). These results led to a voluntary cessation of electrofishing on trophy rainbow trout streams by the Alaska Department of Fish and Game. By contrast, Habera et al. (1996) concluded that short-term mortality and injury rates of rainbow trout in low-conductivity streams in the southern Appalachian mountains were relatively low. Mortality rates for electrofishing were not different than those for fish caught and released by angling. The rate of spinal injuries and/or spinal hemorrhaging was 6%. Rates of injury and mortality for other species, such as northern pike, arctic grayling, and whitefish are not as high as those observed for rainbow trout (Holmes et al., 1990). Comparison of mortality rates between studies should not be made without acknowledging differences in electrofishing gear operation and stream conditions.

While the evidence for short-term effects of electrofishing on individual fish is strong based on numerous studies, there is less indication of long-term effects on individual growth rates. In one study by Dwyer and White (1995), growth rates were depressed in adult rainbow trout, juvenile arctic grayling, and cutthroat trout following exposure to pulsed DC for 10 seconds. In another study, there was no evidence of decreased growth rates or decreased long-term survival of rainbow trout and arctic grayling associated with electrofishing (Holmes et al., 1990). Injuries that increase susceptibility to predation and disease may also be very important, but there is very little data are available to evaluate how frequent and severe this problem may be.

Likewise, there is very little evidence of population-level impacts of electrofishing sampling. Using a hypothetical example in which 95% of fish in the stream were exposed to electrical current in a 500-m reach of a 10-km stream section, Schill (1995) estimated that injury and mortality rates for the entire population of rainbow trout in the 10-km stream section would be 2.4% and 1.2%, respectively. These relatively low values were obtained despite worst-case assumptions of injury and mortality rates of 50% and 25%, respectively.

When considering variability in injury or mortality rates among sampling methods, it is important to consider both the individual injury rate rate and the proportion of the population eventually sampled and the rate of natural mortality by species and age class.

One sampling method may have a higher injury rate than another (0.50 vs. 0.25), but require sampling a smaller proportion of the total population to meet the study objectives (0.10 vs. 0.30); therefore, the total number of affected fish may be lower (5 fish vs. 7.5 fish out of every 100 in the population). Furthermore, without reliable data on probabilities of capture based on mark/recapture experiments, there may be a tendency to overestimate capture efficiency, which in turn could lead to underestimating the population size (Bohlin and Cowx, 1990) and therefore overestimating the injury rate.

Although catch-and-release angling can be very stressful for fish, public perception is that electrofishing is more injurious. This negative public perception and the potential harm to fish populations are both arguments for electrofishing moratoriums. The negative public perception of electrofishing stems largely from the fear of the harmfiul effects of electricity. Within the fisheries biology community, many biologists who lack sufficient training in the theory and practice of electrofishing to assuage this fear, are disturbed by the historic lack of guidelines. The development of guidelines and training programs, coupled with advances in equipment and techniques, will help reduce both injury and mortality rates.

Given the prevalence of electrofishing in fisheries studies, and the lack of attention given to how these methods may affect populations, additional funding should be provided for studies examining the basic underpinnings of electrofishing techniques.

How dangerous is electrofishing in the rain?

In the Pacific Northwest, rain is a regular event. Avoiding electrofishing in the rain reduces the ability to collect data on seasonal changes in fish communities, yet rain clearly introduces a safety consideration. In a draft document, *Electrofishing Code of Practice*, Goodchild (1990) recommends against electrofishing in inclement weather.

Are the safety precautions of assuring that all equipment is grounded, that poles are nonconductive, and that rubber gloves are worn by all personnel sufficient? A standard response for boat electrofishing is that, if an equipotential surface is maintained within the boat, electrofishing can be conducted, unless a continuous sheen of water covers the inside surfaces of the boat (as would occur in hard rain). The continuous sheen of water disrupts the established equipotential surface. Overhanging vegetation in contact with the boat can be carrying a different charge than that in the water; thus, crew members should avoid contact with streamside and overhanging vegetation. Providing crew members with dry effective insulating clothing (neoprene or rubber) is the most effective safety measure and is highly advisable.

There are no known cases of serious injury resulting from electrofishing in the rain. People electrofishing in the rain have reported tingling sensations when their clothes beneath the rubber outwear became wet and they made contact with the boat. People using backpack shockers in the rain have also reported numbness when they were not wearing rubber gloves.

Manufacturers of electrofishing equipment do not recommend electrofishing in the rain, for liability reasons alone. Recognizing that electrofishing in the rain is sometimes conducted, however, they do make every effort to provide as much protection from injury as possible.

The levels of electricity generally encountered when backpack electrofishing using DC are not high enough to be fatal or cause electrocution. The greatest danger is injury from falling when startled by a more moderate shock.

Is electrofishing a science or an art?

Electrofishing is a combination of science and art. The importance of the science (circuit theory and field theory) cannot be overemphasized, particularly with regard to standardizing procedures. Whether electrofishing is a science in the sense that it is reproducible is still an open question. Is it possible to return to a site under the same conditions and same fish population and get the same estimates of fish abundance and population sizes? As better electrofishing protocols are developed by state and federal agencies, the answer to this question is more frequently becoming "yes." Without these protocols however, the answer can often be "no." The art of electrofishing is the ability to operate electrofishing equipment with maximal efficiency, particularly in complex environments. In this sense, electrofishing is a form of skilled labor.

Standardization of electrofishing techniques so that data can be compared among projects by different entities is often not undertaken. In many instances, the information required to do so is not routinely collected or reported, especially on the subject of injury and mortality rates associated with electrofishing. It is also unclear whether standardization has been any more successful for other capture techniques, such as seining or trap netting.

Maximizing efficiency may be possible only for electrofishing programs targeting a specific age class of a single species in a specific habitat. If fish community structure is the objective, then any electrofishing conditions represent a compromise in efficiency relative to individuals, species, and age classes. The fact that a compromise exists means that standardization is necessary, otherwise electrofishing becomes more art than science, and is more dependent on the skill and training of the crew than on technical or biological considerations.

Electrofishing is more difficult to standardize than seining. Some seining parameters, such as net dimensions, mesh size, and length of time in place can be easily standardized. Electrofishing is complicated by the differences in systems among manufacturers, and by the tendency of operators to constantly adjust settings. The difficulty of standardizing electrofishing techniques is also complicated by the fact that conditions vary tremendously among streams and stream reaches. In flowing systems, the wide range of habitat types within and between watersheds demands that a standardized method for evaluating habitat should be used so that habitat variability can be accounted for in species richness and abundance estimates. It almost requires a site-specific calibration approach, which is excessively labor intensive. The sources of variability in electrofishing are so numerous standardization almost seems hopeless at times. Moving toward a goal of standardization requires, at a minimum, identifying the largest sources of variability. In some cases, many of the largest sources of concern with respect to variability can be avoided by undertaken mark/recapture estimates and correcting data with efficiency curves. When depletion methods are used, models such as CAPTURE are able to account for unequal catchabilities.

What information can single-pass electrofishing provide? When is multiple gear appropriate?

Single-pass electrofishing is a common monitoring protocol. There is some concern that species presence cannot be accurately assessed using single-pass methods, particularly with regard to determining relative abundances. The uncertainty with respect to the presence of rare species, or species difficult to catch by electrofishing, is very high. Among other studies, Jones and Stockwell (1995) found that single-pass electrofishing accurately predicted population estimates obtained by multiple-pass electrofishing for stream-dwelling salmonids.

Although electrofishing can capture a tremendous range of fish sizes, it is a size-selective method. Analysis of data by size class can reduce some sources of error. One way to evaluate the influence of size-selectivity is by using multiple gear types. Each method must be standardized and the methods must be sufficiently independent of each other. If the goal of the project is to accurately characterize individual sites, then multiple gear approaches are recommended. If, however, the goal is to compare fish communities among sites, then electrofishing alone may be sufficient.

In single pass aand depletion methods of electrofidhing, the difficulty in interpretation is that the assumption of equal capture efficiencies among sites is probably not valid because of varying environmental conditions. Physical and chemical differences among sites have an enormous impact on electrofishing efficiency. Since these variables are not controllable, every effort should be made to minimize variability associated with electrofishing equipment.

Although electrofishing is not perfect, it is a powerful method for detecting differences among different systems. While estimates of fish densities to the nearest fish/m^2 may not very precise using electrofishing techniques, it is possible to provide sufficient perspective on relative fish population and community structures among sites using established electrofishing techniques. Although variability in environmental parameters overrides the ability to achieve complete standardization, this does not mean that efforts to standardize operations should not be undertaken. Electrofishing efficiency can never be known in advance, but it can be calculated afterwards. Crews will not know how efficient they are going to be beforehand, but they can and should document the parameters affecting their efficiency, which requires a mark/recapture exercise.

What parameters related to electrofishing should be recorded and documented in peer-reviewed manuscripts?

The efficiency of electrofishing is determined by a wide range of factors, which can be grouped into environmental, biological, and technical elements (Zalewski and Cowx, 1990). Capture efficiencies for juvenile Atlantic salmon in New Brunswick streams ranged from <10% to >70%, and were related in part to varying environmental factors (Randall, 1990). However, more than 50% of the variability in capture efficiencies was not explained by environmental factors.

In order to evaluate the electrofishing protocols used in fisheries research and monitoring, it is important to provide information on these factors. Two sets of information should be reported: a set of factors that describe the habitat and fish sampled, and a set of factors that standardize the electrofishing effort.

Habitat and fish community descriptors

1. Substrate type. Substrate type provides an indication of water velocity, and the difficulty of netting fish on the bottom.

2. Sample depth range. Average and maximum water depth of thalweg or in fished area (based on 10+ measurements); in studies in lakes, mean depth had a greater effect on capture efficiencies than conductivity.

3. Water velocity or habitat unit classification. If a USGS gauging station is located close to the site, this flow information should be reported. Mean velocity, however, is meaningless if the sampled area includes a combination of fast and slow waters. Reporting habitat units as a percentage of fished stream area would be useful.

4. Weather conditions. Sun, wind, and rain all produce different effects on visibility for the netter.

5. Size and species of fish

6. Estimates (and confidence of those estimates) of capture efficiency; results from alternative gear sampling.

7. Observational notes on fish that escaped

Technical factors

1. Output voltage

2. Output amperage

3. Output wattage. This is important if sampled sites have a wide range of conductivities.

4. Crew training and experience level

5. Frequency (for pulsed DC systems)

6. Water conductivity (ambient, and specific conductivity)

7. Water temperature

8. Water clarity

9. Effective field size (distance from the anode that voltage gradient is 0.1 V/cm)

10. Gear description. Manufacturer and model of electrofishing unit, electrode configuration and size, generator capacity.

11. Waveform shape. Pulse width and peak voltage.

Although some of these data may not be used directly in statistical analyses, they provide important information for readers to develop aperspective on the study.

Should a licensing process for electrofishing operators be enacted?

Concerns for human safety and potential impact to fish populations suggest a possible benefit from certification of electrofishing crews. The U.S. Fish and Wildlife Service requires all personnel participating in electrofishing either to successfully complete a 3-day course or to achieve a certain score on an independent written test. Some state agencies (e.g., in New York and California) also have certification processes. Agencies in some other states have provisionally adopted the U.S. Fish and Wildlife course until they can adopt their own certification process. More state agencies are becoming interested in enhancing training programs and possible certification. An initial first step may be for the American Fisheries Society to provide a forum for addressing safety considerations for both humans and fish.

7. What is the future of electrofishing?

Some states have recently considered bans or moratoriums on electrofishing practices. The Alaska Department of Fish and Game imposed a voluntary moratorium on electrofishing in streams with trophy rainbow trout, based on mortality rates and complaints by anglers of visible branding (Holmes et al., 1990). State agencies in Montana have placed restrictions on electrofishing, by setting maximum allowable Hz levels (Schill and Beland, 1995). The Oregon Department of Fish and Wildlife has discussed the possibility of a ban, but has no plans for enacting a ban in the near future.

For many research applications, alternative fish-capture techniques such as seining, gillnetting, or trap-netting are less desirable because of potential damage to the fisheries and compromise of data quality. For example, Holmes et al. (1990) found that mortality rates in rainbow trout did not differ among electrofishing, angling (catch and release), and trap netting. Regardless of the method of capture, handling stress can result in a higher incidence of injury and mortality than the capture technique (Holmes et al., 1990). Several studies have evaluated electrofishing relative to other capture techniques for specific studies objectives (see Saltveit, 1990; Growns et al., 1996; Thurow and Schill, 1996).

As professionals who practice electrofishing, we are responsible for assuring ourselves that we employ electrofishing in an appropriate, optimal, and safe manner. This responsibility requires that we (1) evaluate the ability of other capture methods to meet the scientific objectives with a similar or lower rate of mortality, (2) evaluate the capture efficiencies when required to properly interpret study results, (3) optimize electrofishing configurations to minimize the likelihood of fish injury under given environmental conditions, and (4) avoid putting crew members in situations of unacceptable risk of injury. If we educate ourselves, evaluate relative rates of injury and mortality to fish at appropriate levels (e.g., population level), produce information useful for the management of fisheries and their related habitats, and clearly explain the utility of electrofishing data to the public, then the future of electrofishing will be secured.

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List of Abbreviations and Acronyms

AC	alternating current
cm	centimeter
CPS	complex pulse system
CPUE	catch per unit effort
DC	direct current
EMAP	Environmental Monitoring and Assessment Program
EPA	Environmental Protection Agency
hp	horsepower
Hz	hertz
IBI	Index of Biotic Integrity
LTER	Long Term Ecological Research
m	meter
msec	milliseconds
PCF	power correction factor
RMS	root mean square
USFWS	U.S. Fish and Wildlife Service

List of Symbols

D	watt/cm^3
$\mathcal{E}$	volts/cm
I	ampere (amp)
J	amp/cm^2
p (or ρ)	(rho) ohm-cm
R (or Ω)	(omega) ohm
P	power
sigma	mho/cm or µS/cm
V	volt
V_{max}	maximum voltage
V_p	peak voltage
V_{rms}	root mean square voltage
V/cm	volt per centimeter
Q	coulomb
W	watt-hour
µS/cm	micro-Siemens per centimeter

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